| TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG) | MEETING 25<br>11-12 December 2018 |
| --- | --- |
| **PRELIMINARIES**<br>**Welcome and apologies** | **Agenda Item 1.1**<br>**For Information** |

## RECOMMENDATIONS

1. That the RAG **NOTE**:
   a. an opening prayer;
   b. an acknowledgement of Traditional Owners;
   c. the Chair’s welcome address; and
   d. apologies received from members unable to attend.

## BACKGROUND

2. Apologies have been received from Dr Ray Moore (Industry Member) and Mr Mark David (Industry Member and Traditional Inhabitant Kulkalgal).

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| **TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG)** | **MEETING 25**<br>**11-12 December 2018** |
| **PRELIMINARIES**<br>**Adoption of agenda** | **Agenda Item 1.2**<br>**For Decision** |

**RECOMMENDATIONS**

1. That the RAG consider and **ADOPT** the agenda.

**BACKGROUND**

2. A draft agenda was circulated to members on 29 November 2018. Minor comments received have been incorporated.

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| **TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG)** | **MEETING 25**<br>**11-12 December 2018** |
| **PRELIMINARIES**<br>**Declaration of interests** | **Agenda Item 1.3**<br>**For Decision** |

**RECOMMENDATIONS**

1. That RAG members and observers:
    a. **DECLARE** all real or potential conflicts of interest in the Torres Strait Rock Lobster Fishery at the commencement of the meeting (**Attachments 1.3a** and **1.3b**);
    b. **DETERMINE** whether the member may or may not be present during discussion of or decisions made on the matter which is the subject of the conflict;
    c. **ABIDE** by decisions of the RAG regarding the management of conflicts of interest; and
    d. **NOTE** that the record of the meeting must record the fact of any disclosure, and the determination of the RAG as to whether the member may or may not be present during discussion of, or decisions made, on the matter which is the subject of the conflict.

**BACKGROUND**

2. Consistent with the *Protected Zone Joint Authority (PZJA) Fisheries Management Paper No. 1* (FMP1), which guides the operation and administration of PZJA consultative forums, members are asked to declare any real or potential conflicts of interest.
3. RAG members are asked to confirm the standing list of declared interests (**Attachments 1.3a** and **1.3b**) is accurate and provide an update to be tabled if it is not.
4. FMP1 recognises that members are appointed to provide input based on their knowledge and expertise and as a consequence, may face potential or direct conflicts of interest. Where a member has a material personal interest in a matter being considered, including a direct or indirect financial or economic interest; the interest could conflict with the proper performance of the member's duties. Of greater concern is the specific conflict created where a member is in a position to derive direct benefit from a recommendation if it is implemented.
5. When a member recognises that a real or potential conflict of interest exists, the conflict must be disclosed as soon as possible. Where this relates to an issue on the agenda of a meeting this can normally wait until that meeting, but where the conflict relates to decisions already made, members must be informed immediately. Conflicts of interest should be dealt with at the start of each meeting. If members become aware of a potential conflict of interest during the meeting, they must immediately disclose the conflict of interest.
6. Where it is determined that a direct conflict of interest exists, the forum may allow the member to continue to participate in the discussions relating to the matter but not in any decision making process. They may also determine that, having made their contribution to the discussions, the member should retire from the meeting for the remainder of discussions on that issue. Declarations of interest, and subsequent decisions by the forum, must be recorded accurately in the meeting minutes.

**TRLRAG Declarations of Interest from TRLRAG 24 held on 18-19 October 2018**

| Name | Position | Declaration of interest |
|---|---|---|
| **Members** | | |
| Dr Ian Knuckey | Chair | Chair / Director of Fishwell Consulting Pty Ltd and Olrac Australia (electronic logbooks). Chair / member of other RAGs and MACs. Conducts various AFMA and FRDC funded research projects including FRDC Indigenous Capacity Building project. Nil interests in TRL Fishery and no research projects in the Torres Strait.<br>Full declaration of interests provided at **Attachment 1.3b**. |
| Selina Stoute | AFMA Member | Nil. |
| Allison Runck | TSRA Member | Nil. TSRA holds multiple TVH TRL fishing licences on behalf of Torres Strait Communities but does not benefit from them. |
| Danielle Stewart | QDAF Member | Nil. Harvest Fisheries Manager, QDAF. |
| Dr Eva Plaganyi | Scientific Member | Lead scientist for PZJA funded TRL research projects conducted by CSIRO. |
| Dr Andrew Penney | Independent Scientific Member | Research consultant (Pisces Australis), member of other AFMA RAGs (SPFRAG and SESSFRAG). Nil pecuniary or research interests in the Torres Strait. |
| Aaron Tom | Industry Member | Traditional Inhabitant Gudumalulgal and TIB licence holder. |
| Les Pitt | Industry Member | Traditional Inhabitant Kemer Kemer Meriam and TIB licence holder. |
| Phillip Ketchell | Industry Member | Traditional Inhabitant Kaiwalagal, Traditional Owner and fisher. |
| Terrence Whap | Industry Member | Traditional Inhabitant Maluialgal and Traditional Owner. Does not hold a TIB licence. |
| Daniel Takai | Industry Member | Pearl Island Seafoods, Tanala Seafoods, TIB licence holder and lessee of TSRA TVH licence in 2017/18 fishing season. |
| Brett Arlidge | Industry Member | General Manager MG Kailis Pty Ltd. MG Kailis Pty Ltd is a holder of 5 TVH licences. |
| Natalie Couchman | Executive Officer | Nil. |

| Observers | | |
|---|---|---|
| Joseph Posu | PNG National Fisheries Authority (NFA) | Nil. |
| Mark Tonks | Scientific observer | Project staff for PZJA funded TRL research projects conducted by CSIRO. |

**Declaration of interests**
**Dr Ian Knuckey – October 2018**

**Positions:**

| | |
|---|---|
| Director – | Fishwell Consulting Pty Ltd |
| Director – | Olrac Australia (Electronic logbooks) |
| Deputy Chair – | Victorian Marine and Coastal Council |
| Chair / Director – | Australian Seafood Co-products & ASCo Fertilisers (seafood waste) |
| Chair – | Northern Prawn Fishery Resource Assessment Group |
| Chair – | Tropical Rock Lobster Resource Assessment Group |
| Chair – | Victorian Rock Lobster and Giant Crab Assessment Group |
| Scientific Member – | Northern Prawn Management Advisory Committee |
| Scientific Member – | SESSF Shark Resource Assessment Group |
| Scientific Member – | Great Australian Bight Resource Assessment Group |
| Scientific Member – | Gulf of St Vincents Prawn Fishery Management Advisory Committee |
| Scientific participant – | SEMAC, SERAG |

**Current projects:**

| | |
|---|---|
| AFMA 2018/08 | Bass Strait Scallop Fishery Survey – 2018 and 2019 |
| FRDC 2017/069 | Indigenous Capacity Building |
| FRDC 2017/122 | Review of fishery resource access and allocation arrangements |
| FRDC 2016/146 | Understanding declining indicators in the SESSF |
| FRDC 2016/116 | 5-year RD&E Plan for NT fisheries and aquaculture |
| AFMA 2017/0807 | Great Australian Bight Trawl Survey – 2018 |
| Traffic Project | Shark Product Traceability |
| FRDC 2018/077 | Implementation Workshop re declining indicators in the SESSF |
| FRDC 2018/021 | Development and evaluation of SESSF multi-species harvest strategies |
| AFMA 2017/0803 | Analysis of Shark Fishery E-Monitoring data |
| AFMA 2016/0809 | Improved targeting of arrow squid |

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| **TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG)** | **MEETING 25**<br>**11-12 December 2018** |
| **PRELIMINARIES**<br>**Action items from previous meetings** | **Agenda Item 1.4**<br>**For Decision** |

**RECOMMENDATIONS**

1. That the RAG:
    a. **ADOPT** the final meeting record for TRLRAG 24 held on 18-19 October 2018 (**Attachment 1.4a**).
    b. **NOTE** the progress against actions arising from previous meetings (**Attachment 1.4b**).

**BACKGROUND**

*Meeting record*

2. The draft meeting record for TRLRAG 24 held on 18-19 October 2018 was provided out of session for comment on 31 October 2018. No comments were received.
3. The final meeting record is provided at **Attachment 1.4a**.

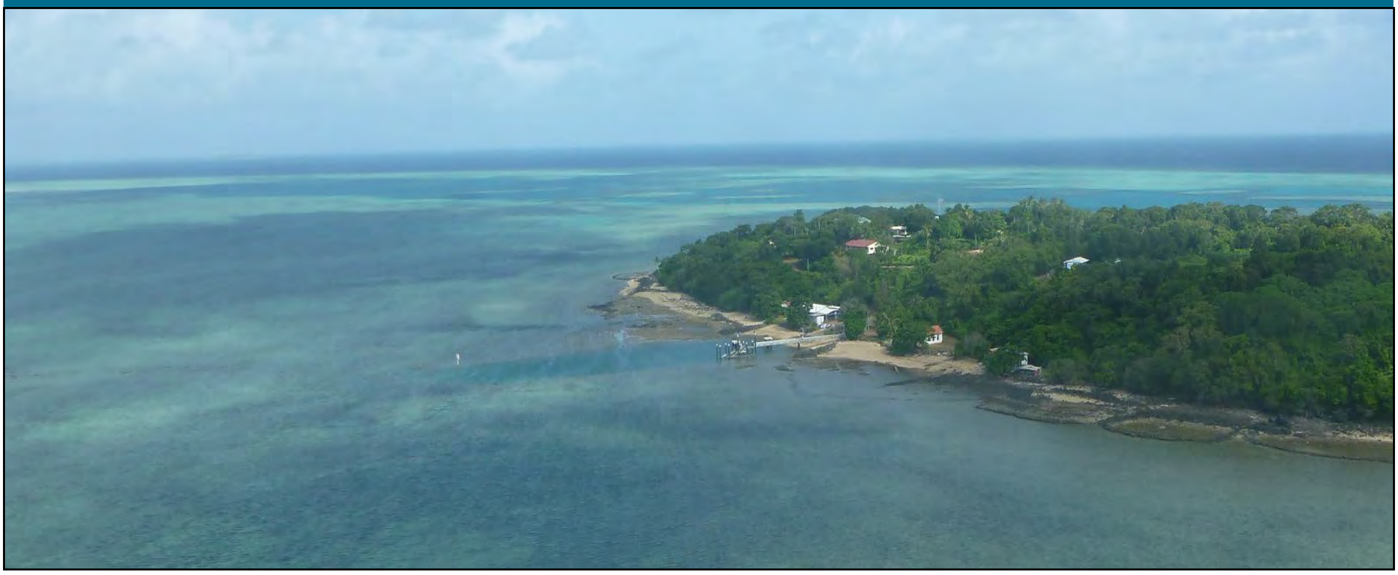
*Actions arising*

4. Updates are provided on the status of actions arising from previous TRLRAG meetings and relevant TRLWG meetings at **Attachment 1.4b**.

# Rolling Five Year Research Plan

# 2019/20-2022/23

## DRAFT Torres Strait Tropical Rock Lobster Fishery



**Compiled by AFMA**

**October 2018**

## ABOUT THIS PLAN

The Torres Strait Scientific Advisory Committee (TSSAC) seeks input from each fishery advisory body (Resource Assessment Group (RAG), Management Advisory Committee (MAC) or Working Group (WG)) to identify research priorities over five year periods from 2019/2020 to 2022/23. This template is to be used by the relevant advisory body to complete their five-year plan. The plans are to be developed in conjunction with the TSSAC Five-year Strategic Research Plan (SRP) with a focus on the three research themes and associated strategies within the SRP.

All fishery five-year plans will be assessed by the TSSAC using a set of criteria, and used to produce an Annual Research Statement for all Torres Strait fisheries.

The TSSAC then develop scopes for the highest ranking projects in order to publish its annual call for research proposals. There are likely to be more scopes that funding will provide for so TSSAC can consider a number of proposals before deciding where to commit funding.

The fishery five-year plans are to be reviewed and updated annually by the Torres Strait forums to add an additional year onto the end to ensure the plans maintain a five year projection for priority research. Priorities may also change during the review if needed.

# RESEARCH PRIORITIES

**Table 1.** Five year Torres Strait Tropical Rock Lobster Fishery research plan for 2018/19 – 2022/23.

| Proposed Project | Objectives and component tasks | Year project to be carried out and indicative cost* | | | | | | Other funding bodies[1] | Evaluation | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 2018/19 | 2019/20 | 2020/21 | 2021/22 | 2022/23 | Notes on project timings | | Priority essential /desirable | Priority ranking (1-5 – 1 being highest priority) | Theme |
| Fishery surveys, stock assessment, harvest control rules and recommended biological catch (RBC) | Monitor ongoing changes in the fishery and update or develop fishery performance indicators as required; Recommend a recommended biological catch (RBC) annually for each season; Every third year update and implement the long-term stock assessment; Conduct a pre-season survey in November each year, including seabed habitat monitoring; Continue development of a harvest | 277,477 (funded under 2016/ 0822) | 260,000 | 240,000 | 240,000 | 240,000 | Nil | AFMA<br>CSIRO<br>PNG<br>NFA<br>Industry | Essential | 1 | 1 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | strategy for the TRL Fishery including an empirical harvest control rule. Facilitate data sharing with PNG. Development of a tiered harvest strategy for the TRL Fishery. | | | | | | | | | | |
| Mid-year survey | Conduct mid-year survey, as required under the Harvest Strategy for the TRL Fishery | 0 | 0 | 0 | 0 | 0 | To be conducted on an as needs basis – indicative cost $110,000 with in-kind contribution from CSIRO | AFMA CSIRO PNG NFA Industry | Essential (when required) | 1 | 1 |
| ~~Stock assessment~~ Science peer review | Consistent with best practice Guidelines for quality assurance of Australian fisheries research and science information (the Guidelines), a peer review be conducted of the TRL Fishery survey design, stock assessment | 0 | ~~1~~60,000-~~3~~80,000 (dependent on final scope) | 0 | 0 | 0 | Terms of reference to be developed and considered by the RAG in first quarter of 2019 | AFMA | ~~Desirable~~ Essential | ~~3~~1 | 1 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | and draft Harvest Strategy. | | | | | | | | | | |
| Ecological risk assessment (ERA) | Conduct an update to the 2007 ERA for the TRL Fishery. | 0 | 20,400 | 0 | 0 | 0 | To be conducted in the next three years | AFMA CSIRO | Desirable Essential | 31 | 1 |
| Tiered harvest strategy | Development of a tiered harvest strategy for the TRL Fishery. | TBA | TBA | TBA | TBA | TBA | Nil | | Desirable | 3 | 1 |
| Continuation and iImprovement of data collection | Improved monitoring of commercial catch and effort in all sectors of the fishery; Estimate of non-commercial take of TRL; Alternative monitoring techniques of effort, for example GPS tracking.; Understanding the effect of the use of hookah on recruitment of stock on shallow reefs. | 0 | 20,000 | 0 | 0 | 0 | Sub-group of the RAG to progress alongside upcoming RAG meetings – funding for sub-group meetings to be sourced from RAG budget | AFMA PNG NFA | Desirable Essential | 51 | 1,3 |
| Understanding connectivity, environmental drivers and adaptation strategiesMovement | Understanding of migration of settled lobster between, and within, jurisdictions. | 0 | 0 | TBA | TBA | TBA | Nil | AFMA PNG NFA CSIRO | Desirable Essential | 52 | 1 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ~~and recruitment connectivity between areas within Torres Strait and between Torres Strait and neighbouring jurisdictions, including QLD and PNG~~ | ~~e.g. linkages between deep and shallow and among reefs~~; Understanding of recruitment connectivity between, and within, jurisdictions; Management implications of movement and recruitment connectivity between, and within, jurisdictions. | | | | | | | | | | |
| Understanding changes to fishing power ~~over~~ through time | Understanding changes in fishing behaviour and power over time (e.g. changes to the size of engines, use of GPS, gear, areas fished, time fished, experience of divers), to inform the standardisation of CPUE data. | 0 | 0 | TBA | TBA | TBA | Sub-group of the RAG to progress once progress on improving data collection has been made – funding for sub-group meetings to be sourced from RAG budget | AFMA CSIRO | Desirable | ~~5~~2 | 1 |
| Understanding fishing behaviour | Understanding the drivers and incentives in determining fishing behaviour in all sectors; | 0 | TBA | TBA | TBA | TBA | Timing of project to be considered once a Management Plan has been fully | AFMA | Desirable | ~~5~~3 | 1 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Understanding fishing behaviour under output controls: the impact of ITQs or competitive quota on the fishery; the extent and impact of discard mortality; the effect of changing market preferences on fishing behaviour under output controls; the extent of value adding e.g. moving to live product, targeting different sizes; the extent of high grading under output controls. | | | | | | implemented in the TRL Fishery | | | | |
| ~~Environmental impacts~~ | ~~Collect relevant baseline information to assess environmental change impacts on TRL populations; Analyse the impact of~~ | ~~TBA~~ | ~~TBA~~ | ~~TBA~~ | ~~TBA~~ | ~~TBA~~ | ~~Nil~~ | | ~~Desirable~~ | ~~5~~ | ~~1~~ |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ~~environmental change on the TRL Fishery.~~ | | | | | | | | | | |

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Australian Fisheries Management Authority

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# Meeting participants

## Members

| Name | Position | Declaration of interest |
|---|---|---|
| Dr Ian Knuckey | Chair | Chair/Director of Fishwell Consulting Pty Ltd and Olrac Australia (electronic logbooks). Chair/member of other RAGs and MACs. Conducts various AFMA and FRDC funded research projects including FRDC Indigenous Capacity Building project. Nil interests in TRL Fishery and no research projects in the Torres Strait.<br>Full declaration of interests provided at **Attachment A**. |
| Natalie Couchman | AFMA Executive Officer | Nil. |
| Selina Stoute | AFMA member | Nil. |
| Allison Runck | TSRA member | Nil. TSRA holds multiple TVH TRL fishing licences on behalf of Torres Strait Communities but does not benefit from them. They will not be leased in the 2018/19 fishing season. |
| Danielle Stewart | Queensland Department of Agriculture and Fisheries (QDAF) member | Nil. Harvest Fisheries Manager, QDAF. |
| Dr Andrew Penney | Scientific member | Research consultant (Pisces Australis), member of other AFMA RAGs (SPFRAG and SESSFRAG). Nil pecuniary or research interests in the Torres Strait. |
| Dr Éva Plagányi | Scientific member | Lead scientist for PZJA funded TRL research projects conducted by CSIRO. |
| Aaron Tom | Industry member | Traditional Inhabitant Gudumalulgal and TIB licence holder. |
| Les Pitt | Industry member | Traditional Inhabitant Kemer Kemer Meriam and TIB licence holder. |
| Phillip Ketchell | Industry member | Traditional Inhabitant Kaiwalagal, Traditional Owner and fisher. |
| Mark David | Industry member | Traditional Inhabitant Kulkalgal and TIB licence holder. |

| Name | Position | Declaration of interest |
|---|---|---|
| Daniel Takai[+] | Industry member | Pearl Island Seafoods, Tanala Seafoods, TIB licence holder and lessee of TSRA TVH licence in 2017/18 fishing season. |
| Brett Arlidge | Industry member | General Manager MG Kailis Pty Ltd. MG Kailis Pty Ltd is a holder of 5 TVH licences. |

## Observers

| Name | Position | Declaration of interest |
|---|---|---|
| John Kris | Representative for Malu Lamar (Torres Strait Islanders) Corporation Registered Native Title Body Corporate (RNTBC) | Trustee responsible for administering the native title rights over 44,000 $km^2$ of seas on behalf of the Torres Strait Islander claimants represented in the Torres Strait Regional Sea Claim determination of 2010. |
| Joseph Posu* | PNG National Fisheries Authority (NFA) | Nil. |
| Dr Robert Campbell | CSIRO scientific observer | Nil pecuniary interests. Project staff for PZJA funded TRL research projects. |
| Dr Tim Skewes | Scientific observer | Hand Collectables Working Group member, involved in research in the Torres Strait since 1987. Project staff for PZJA funded TRL (surveys) and BDM research projects. |
| Jerry Stephen[~] | TSRA Deputy Chair, TSRA Member for Ugar and TSRA Portfolio Member for Fisheries | TIB licence holder and Native Title holder. |
| Trent Butcher[#] | Industry observer | TVH licence holder. |
| Patrick Mills | Chair of Torres Strait Fisher's Association (TSFA) | TIB licence holder and Traditional Owner. |
| Suzannah Salam | Industry observer | Torres Straits Seafood Pty Ltd, TIB licence holder and lessee of TSRA TVH licence in 2017/18 fishing season. |
| Tony Salam^ | Industry observer | Torres Straits Seafood Pty Ltd, TIB licence holder and lessee of TSRA TVH licence in 2017/18 fishing season. |

Notes:

+ Arrived at 9:10 am on 19 October 2018, partway through Agenda Item 8.

* Attended on 19 October 2018 only.

~ Attended on 18 October 2018 only. Arrived at 8:30 am on 18 October 2018, partway through Agenda Item 1.4.

# Attended on 18 October 2018 only. Departed meeting at 4:00 pm partway through Agenda Item 6.

^ Arrived at 8:40 am on 18 October 2018, partway through Agenda Item 1.5.

# 1 Preliminaries

## 1.1 Apologies

1. The meeting was opened in prayer at 8:15 am on 18 October 2018.
2. The Chair welcomed attendees to the 24th meeting of the Torres Strait Tropical Rock Lobster Resource Assessment Group (TRLRAG 24). The Chair acknowledged the Traditional Owners of the land on which the meeting was held and paid respect to Elders past and present.
3. Attendees at the RAG are detailed in the meeting participant tables at the start of this meeting record.
4. Apologies were received from Mr Terrence Whap (Industry Member and Traditional Inhabitant Maluialgal) and Dr Ray Moore (Industry Member). The RAG noted that Dr Moore provided written comments for consideration under Agenda Items 4-6.
5. The Chair noted that the low recommended biological catch (RBC) and changes to management arrangements during the 2017/18 fishing season had social and economic impacts on communities across the region. The purpose of the meeting is to critically review and discuss how to improve the data, survey and stock assessment that underpins the management of the Torres Strait Tropical Rock Lobster Fishery (the TRL Fishery).

## 1.2 Adoption of agenda

6. The draft agenda was adopted with the addition of a presentation from Dr Andrew Penney, which was presented prior to Agenda Item 4 (**Attachment B**).

## 1.3 Declaration of interests

7. The Chair stated that as outlined in Protected Zone Joint Authority (PZJA) Fisheries Management Paper No. 1 (FMP1), all members of the RAG must declare all real or potential conflicts of interest in the TRL Fishery at the commencement of the meeting. Declarations of interests were provided by each meeting participant. These are detailed in the meeting participant tables at the start of this meeting record.

## 1.4 Action items from previous meetings

8. The RAG noted the status of actions arising from previous TRLRAG, and where relevant, TRL Working Group (TRLWG) meetings (**Attachment C**).
9. The RAG adopted the final meeting records for TRLRAG 22 held on 27-28 March 2018 and TRLRAG 23 held on 15 May 2018 as true and accurate records of these meetings.

## 1.5 Out-of-session correspondence

10. The RAG noted out-of-session correspondence on RAG matters since the previous meeting.

# 2 Updates from members

## 2.1 Industry and scientific

11. The RAG noted updates provided by industry and scientific members and observers on the performance of the TRL Fishery in the 2017/18 fishing season and key issues:
    a. A Traditional Inhabitant Boat (TIB) industry member noted that there were “hotspots” of TRL encountered during the season. Between Thursday Island and Badu, there were very few TRL. Mabuiag yielded good catch rates in the early part of the season. Catch rates were also good towards the east around Warrior Reef in the later part of the season. The member queried whether the survey is covering enough of the TRL grounds to give a good indication of abundance. The member also noted that it is known there are environmental factors which affect the abundance of the stock and if weather systems

are changing, this needs to be taken into account with where the safeguards are set for the Fishery.

b. Another TIB industry member advised that that there was a movement of TRL from the western to the eastern parts of the Fishery during the season. Catch rates were very low particularly around Erub and Mer, uncertain about Ugar. There were reports of good catches around Masig, but he did not experience them himself.

c. An industry member and TRL buyer noted that the TRL taken at Masig were similar to those taken around Warraber and Poruma. These TRL were taken in shallow waters during the period when the use of hookah gear was prohibited. The catch rates in these areas were not higher than average. The member noted that the RAG is responsible for the advice put to the PZJA on the status of the TRL stock for the 2017/18 season. The member observed it was a poor season in some areas, and it was only the hotspots in certain areas that yielded normal catch rates. Given the variable nature of the TRL stock, in some years industry will need to make a sacrifice and the 2017/18 season was that sacrifice. The member looks forward to working with the RAG to improve the science behind the management of the Fishery.

d. Another TIB industry member advised that the catches reported around Masig, Warraber and Poruma were actually taken around Warrior Reef and landed to fish receivers on these islands. The member noted that they did not see many 1+ TRL on the reef edges. The member also fished Dungeness and catch rates were low. The member questioned whether the TRL around Warrior Reef migrated from Kirkcaldie and Dungeness. There is a lot of sand movement in that area.

e. A Transferable Vessel Holder (TVH) industry observer noted that they fished through the season from Mabuiag through to Warrior Reef using hookah gear. The member saw a lot of 0+ TRL around clumps of stones out in the paddocks (7-12 m). This was confirmed by another industry member. A further industry member advised they saw a lot of 0+ lobsters on the reef tops from February until when the mid-year survey was undertaken.

f. Another TIB industry member queried why the far western area of the Fishery is not surveyed, noting this may be a source of TRL for the Fishery.

g. A TVH industry observer advised that they did not have a problem catching TRL at all during the season. The member caught lots of 2+ and saw lots of 0+ TRL during the season. The member noted that a lot of the Torres Strait is too dirty to dive or too far from anchorage. Noting the area fished is small compared to the distribution of TRL, the member questioned whether the survey and stock assessment accurately estimated TRL stock abundance.

h. Another TVH industry member and TRL buyer noted that the RAG previously expected the 2+ TRL would run out in the later part of the season and that there would not be many 1+ TRL coming through. However, when the member looks at the size distribution data from the TRL they bought, the data is consistent with previous seasons and overall catches in particular were similar to 2016, 2014 and 2013. The 2017/18 season was a better season than the 2016/17 season. In the member's view, the 2017/18 season was normal, not the poor season predicted by the survey and stock assessment. The member estimates that $16M worth of TRL was left in the water, of this $9-10M would have gone to TIB fishers. The member was of the view that the survey did not provide an accurate estimate of TRL stock abundance and suggested that the Fishery be managed through input controls until concerns with the survey and stock assessment can be resolved.

i. The Chair noted that at the last RAG meeting, members discussed significant temporal and spatial problems with the catch per unit effort (CPUE) data obtained from fishers. Current CPUE data may also be confounded by a hyper-stability effect, seen when fishers remain on fishing hotspots or move from one hotspot to another – thereby maintaining high catch rates that don't represent the population size of the entire stock. The Chair also advised that the draft Harvest Strategy for the Fishery is designed to leave 65% of the TRL stock in the water each season to provide for natural mortality, spawning, and traditional fishing. This means fishers should see TRL left in the water, as they should only be taking a small proportion of the overall stock.

j. The CSIRO scientific member commended the industry and government for ensuring catches remained within the RBC for the Fishery. The member cautioned the RAG to not throw out 50 years of really good science backing up this Fishery on the basis of one season's experience. The member noted that they will provide analyses of both survey and industry data at this meeting, but noted that members need to keep in mind that industry target certain sized TRL. CSIRO are able to look at industry data in more detail in the coming months if desired.

## 2.2 Government

12. The RAG noted an update provided by the AFMA member regarding management initiatives relevant to the TRL Fishery:

    a. 2017/18 fishing season management summary – additional moon-tide hookah closures commenced on 13 April 2018 followed by a prohibition on the use of hookah gear for the remainder of the season commencing 30 April 2018. The intent of these management changes was to give effect to the TRLWG recommendations that catches should not exceed the RBC and to prolong the season. The decision to prohibit the use of hookah gear was successfully challenged by Malu Lamar through the Federal Court. The decision was quashed and arrangements reverted to the additional moon-tide hookah closures. Fishers caught the Australian catch share of the RBC, 254.15 tonnes, by 30 July 2018 and the Fishery was closed for the remainder of the season. Further details are provided in an attachment to the paper for this Agenda Item.

    b. Outcomes of the Federal Court case – on 27 June 2018, his Honour Justice Rares of the Federal Court of Australia quashed the decision of the CEO of AFMA, as delegate of the PZJA, to implement a prohibition on the use of hookah gear. His Honour found that the delegate was obliged to afford procedural fairness to Malu Lamar prior to making the decision to amend licence conditions, but had failed to do so on the basis that Malu Lamar's response to a native title notification had not been considered by the delegate prior to making the decision. His Honour's judgement did not consider the merits of the AFMA CEO's decision itself.

    c. Change of Commonwealth fisheries Minister - Senator the Hon. Richard Colbeck has replaced Senator the Hon. Anne Ruston as the Assistant Minister for Agriculture and Water Resources. In this position, Senator Colbeck will serve as the Chair of the PZJA.

    d. Australian National Audit Office (ANAO) audit - the ANAO is currently undertaking a performance audit of the coordination arrangements of Australian Government agencies operating in the Torres Strait. A report is due to be tabled in January 2019.

    e. Catch sharing arrangements with PNG – PNG has provided monthly catch data. The AFMA CEO has met with the Managing Director of the PNG NFA regarding the status of catch sharing arrangements, noting the PNG fishery remains open. A TVH industry member advised that the PNG NFA has written to operators to prohibit fishing in PNG waters inside the Torres Strait Protected Zone (TSPZ), but not the area outside. AFMA are also working with the PNG NFA to reach more timely agreement on catch sharing arrangements each season.

    f. Proposed TRL Management Plan – in August 2018, AFMA circulated a media release from Senator Ruston concerning the implementation of a Management Plan by 1 December 2018. Noting Senator Colbeck has since replaced Senator Ruston, Senator Colbeck and Mr Napau Pedro Stephen are meeting today to discuss the implementation of a Management Plan further, including a proposal to implement a sectoral split (based on that proposed under the Management Plan) for the 2018/19 fishing season. The PZJA is likely to meet again soon to give further direction. AFMA continues to operate under the previous direction to implement a Management Plan by 1 December 2018 while awaiting further advice.

13. Noting concerns from members that 1 December 2018 is only a few weeks away, the AFMA member explained that the quota management system will take time to implement following the determination of the Management Plan. Once the Management Plan is determined, there is an

allocation process that will need to be completed before quota units can be formally allocated and this process can take months to years, depending on appeals.

14. The RAG noted an update provided by the TSRA member regarding TSRA activities relevant to the management of the TRL Fishery:
    a. Fisheries Summit – a Fisheries Summit was held on Thursday Island in August 2018. One of the main items for discussion was the proposed TRL Management Plan. A resolution was passed by attendees at the Summit for the sectoral split proposed under the Management Plan to be implemented for the 2018/19 fishing season. TSRA has established a TSRA Standing Committee, which first met in September 2018, to oversee the TSRA's engagement in implementing the Management Plan including the establishment of an independent entity to manage the fisheries assets the TSRA holds in trust on behalf of TIB fishers. The TSRA will be conducting community visits in November 2018 to provide information on the Management Plan. New members on PZJA forums were nominated and their terms are to start on 1 January 2019.
    b. Export and branding for Torres Strait seafood - a project is underway to assess the economic feasibility, regulatory requirements and infrastructure needs to export seafood directly from the Torres Strait and the potential value derived from creating a brand for Torres Strait seafood. This project is expected to be finalised by the end of this year. One resource to come out of this project will be exporter handbooks detailing information on supply chains and how to access markets.
15. The RAG noted an update provided by the QDAF member regarding activities in Queensland relevant to the management of the TRL Fishery:
    a. Catches in the East Coast TRL Fishery – see below. Only 84% of the TAC was caught in the 2018 season. An industry member advised that catch rates were better in the Torres Strait TRL Fishery and so a number of fishers remained fishing in the Torres Strait until the Fishery closed. Further, fishers in the East Coast TRL Fishery did not see a walk-in of large numbers of TRL in July through August which is expected each year. Weed was prevalent which is not a preferred habitat for TRL. An industry observer noted that the experience of divers in the East Coast TRL Fishery was also low this season and the "no-cray-itis" effect probably played a part, whereby it was difficult to catch TRL resulting in divers losing motivation in the later part of the season. The QDAF member noted that the TAC isn't normally caught each year. The Fishery is closed between October to December every year.

| Year | Catch (tonnes) | Catch (as a per cent of the 195 tonnes TAC) |
|---|---|---|
| 2009 | 183 | 94 |
| 2010 | 129 | 66 |
| 2011 | 147 | 75 |
| 2012 | 157 | 81 |
| 2013 | 166 | 85 |
| 2014 | 176 | 90 |
| 2015 | 125 | 64 |
| 2016 | 194 | 100 |
| 2017 | 195 | 100 |
| 2018 | 160 | 82 |

    b. East Coast TRL Working Group – the third meeting will take place in December 2018 and will look at a draft Harvest Strategy for the East Coast TRL Fishery. The Fishery is currently managed under a quota management system.

## 2.3 PNG NFA

16. As the PNG NFA representative was not in attendance on 18 October 2018, an update was provided during the following day and is presented later in the minutes.

## 2.4 Native Title

17. The Malu Lamar representative advised that they did not have any updates to provide.

# 3 Catch summary for the 2017/18 fishing season

18. The RAG noted the Australian and PNG catch data for the 2017/18 fishing season:
    a. Australian Torres Strait TRL Fishery - as reported through the mandatory fish receiver system, implemented on 1 December 2017, the reported landed catch for the Fishery for the period 1 December 2017 to 30 July 2018 was 261,067 kg. This equates to 102.72 per cent of the 254.150 kg Australian share of the RBC.
    b. PNG TRL Fishery - the reported catch for the Fishery taken from the TSPZ for the period 1 January 2018 to 21 September 2018 was 66,361 kg. The reported catch for the Fishery taken from outside of the TSPZ for the same period was 2,302 kg. The PNG share of the RBC for the 2017/18 fishing season was 44,850 kg.
19. The RAG expressed appreciation to the PNG NFA in providing the catch data. The RAG noted advice from the CSIRO scientific member that these catches will be factored into the stock assessment for the 2018/19 fishing season, but it would be unlikely to have a big effect as the catches in 2017/18 are of a different age class to that to be caught in the 2019/19 season.

# Presentation from Dr Andrew Penney

20. The RAG considered a presentation provided by Dr Andrew Penney, independent scientific member, detailing Dr Penney's independent interpretation of the data pertaining to the perceived mismatch between TRL survey results and catch rates in the 2017/18 fishing season. These interpretations drew on the analyses conducted in a number of CSIRO papers[1]. Main points discussed:
    a. Some in industry have expressed concerns to AFMA and the RAG that the survey and stock assessment may be misaligned with actual abundance in the 2017/18 fishing season.
    b. 2018 mid-year survey 2+ index - the standard reference sites produced a 2+ index below the value predicted by the stock assessment from the 2017 pre-season 1+ index. The index has been similarly low in a couple of previous years, in particular 1999-2001. Although additional random survey sites were conducted during the mid-year survey in areas generally around hotspot commercial fishing locations, the resulting estimated 2+ index was lower than if those extra sites had not been included. Possible explanations include either the survey sites were not exactly where the hotspots were or the hotspots were short lived aggregations and had disappeared by the time the survey was conducted.
    c. TVH and TIB catch by area – for the TVH sector, 49% of effort in the Northern area produced 47% of the TVH catch (~62t). Mabuiag contributed a further 15% of catch (~20t). The contribution by the Northern area has increased substantially in recent years. For the TIB sector, Mabuiag and Badu contributed more than in recent years but there is uncertainty in the data as to where catches are taken versus landed.

[1] Plagányi E et al. 2018. *Torres Strait TRL 2018 Midyear Survey Summary Report*; Campbell R et al. 2018. *Torres Strait Rock Lobster Fishery – Summary of the Catch and Effort Data pertaining to the 2018 Fishing Season (Dec-17 to Jul-18)*; and, Plagányi E et al. 2018. *Final 2017 Integrated Stock Assessment and RBC (2018) for the Torres Strait rock lobster fishery*

d. Nominal CPUE - does seem to indicate that catch rates in 2017/18 were reflective of an average season, but requires standardisation to take into account increases in fishing efficiency over time. If this is not accounted for in the CPUE standardisation, the CPUE index may overestimate biomass.

e. CPUE relationship with biomass – if the relationship is linear, when CPUE decreases it is assumed that biomass is also decreasing. However, the correlation varies depending on the stock. CPUE for some stocks will show some degree of 'hyper-stability', remaining high during initial stock decline, and then declining more rapidly as the stock declines further. This occurs in TRL given the aggregating nature of the stock, and the stock assessment model assumes a hyper-stable relationship for both sectors of the Fishery. This means that effects of fishing are difficult to detect, with CPUE remaining high despite a stock declining. This has been seen in stocks across the globe, including orange roughy, Californian sardine and Tasmanian abalone.

f. TRL Harvest Strategy (current and draft) - aims to achieve a biomass target ($B_{TARG}$) of 65% of $B_{1973}$. The target fishing mortality rate ($F_{TARG}$) is 0.15. With an estimated natural mortality (M) of 0.69, this equates to an annual natural mortality of 50% and an annual exploitation (fishing) rate of 10%. After natural and fishing mortality is taken into account the Harvest Strategy aims to leave at least 40% of TRL in the water each season. A large proportion of the natural mortality, is not the lobsters dying, but instead lobsters migrating out of the Fishery.

g. There is a high correlation between pre-season and mid-year surveys and different numbers of survey sites used.

h. There is no evidence that the surveys have given biased results, they provide a reliable index of abundance for use in stock assessments. However, given the aggregating nature of TRL, there is a possibility that a survey will miss some aggregations and find others, potentially under or over estimating abundance in particular years.

i. CPUE on such aggregations can be highly stable despite declining abundance. CPUE from large aggregations may not provide a reliable index of abundance. Where a survey has missed such an aggregation, but the industry has found it, there will be a mismatch between apparent abundance seen by the survey and by industry. This seems to be what happened in the 2017/18 fishing season. If such aggregations are made up of lobsters derived from the assessed stock, high CPUE on an aggregation does not indicate a problem with the survey. But if aggregations are made up of lobsters not assessed, this is an issue.

j. There is a trade-off between cost and precision in conducting more surveys or including more sites in existing surveys.

k. Improvements:
    i. CPUE – better data needed to understand efficiency increases and whether there is evidence of aggregation-induced hyper-stability.
    ii. Survey – are there areas being consistently fished that are not being surveyed (e.g. survey and fishing footprints are not aligned) or has the distribution of the stock changed that these areas are not being surveyed?
    iii. Harvest Strategy – should a harvest control rule (HCR) be adopted that provides greater TAC stability e.g. averaging over more years.
    iv. Stratum – TRL04 logbook/TDB02 catch disposal record (CDR) and survey stratum should be standardised.

# 4 Catch and CPUE analyses for the 2017/18 fishing season

21. The RAG considered presentations provided by Dr Robert Campbell, CSIRO scientific observer, detailing analyses of catch and effort data pertaining to the TRL Fishery for the 2017/18 season[2]:

[2] Campbell R et al. 2018. *Torres Strait Rock Lobster Fishery – Summary of the Catch and Effort Data pertaining to the 2018 Fishing Season (Dec-17 to Jul-18)*; Campbell R et al. 2018. *Use of TVH Logbook Data*

a. Data informing the analysis was received in late September 2018. There are three sources of data drawn on for the analysis:
    i. the TRL04 logbook - mandatory for TVH licence holders only;
    ii. TDB01 docket book - voluntary for all licence holders, no longer in use; and
    iii. TDB02 CDR - mandatory for all licence holders, replaced the TDB01 docket book from 1 December 2018.
b. Catch by season (both sectors) – catch in the 2017/18 season was the lowest since 2009. The RAG noted a small difference between the TRL04 logbook and TDB02 CDR records for the TVH sector, likely due to the fact that TRL04 logbook weights are often estimated compared to more accurate weighing on land in a TDB02 CDR.
c. Catch by month (both sectors) – TVH catch was notably constrained by management controls introduced in May and June.
d. TVH sector catch and effort data from February-July 2018:
    i. Catch by method and process - the TVH sector predominantly uses the hookah method, with a small amount of free-diving occurring in the 2017/18 season. The processing form has not changed significantly.
    ii. Location of fishing - the location of fishing in the 2017/18 season was further north than in 2016/17. The RAG noted that it is the location where the primary boat is anchored which is generally recorded, not the location where tenders are actually fishing (which can range as far as 20 nm from the primary boat). Historically, when catches are good, spatial coverage is high. However, spatial coverage in the 2017/18 season was one of lowest. Finer scale (e.g. at the tender level) location data is needed to inform future analysis.
    iii. Areas fished by month – the Northern and Mabuiag areas accounted for 32-62% of data records in 2018.
    iv. Effort (hours fished) by area fished - 47% of total effort has been in the Northern area, 18% in the Warrior area, 15% in the Mabuiag area, and 12% in the Warraber area in 2018.
    v. Catch by area fished - 47% of total catch has been in the Northern area and 18% in the Warrior area. There was increase in catch in the Northern area in the 2017/18 season, but this pattern has been seen in the past. Generally there is a spatial shift each year on where catch is taken. For example, in 2015, large sand incursions in the Northern area, meant not much catch was taken out of this area.
    vi. Catch by hours fished - compared to the previous two seasons, during the 2017/18 season a higher proportion of the catch was been taken on sets with effort of more than 6 hours. Industry members advised that the depth of water determines the hours that can be fished each day (e.g. at 7m depth a diver can fish as long as there is daylight, but the deeper the dives, the more constrained a diver is). The RAG also discussed the 'hours fished' measure used in the TRL04 logbook is being reported inconsistently across fishers (e.g. hours the tender spends away from the boat, hours divers are in the water).
    vii. Nominal CPUE by month and season – generally CPUE decreases after February. In the 2017/18 season CPUE was similar across March, April and June. The mean CPUE in March and April was 28.4% lower than in February (whereas the average decrease over the previous 6 years between 2012 and 2017 was 7.6%). Very little TVH fishing took place in May 2018.
    viii. Nominal CPUE by area and season – across all areas, the mean CPUE in 2018 of 13.1kg/hour is lower than the mean catch rates over the previous 6 years (15.4kg/hour), though slightly higher than in 2016/17 (10.7kg/hour).

*to construct an Annual Abundance Index for Torres Strait Rock Lobster – 2018 Update*; Campbell R et al. 2018. *Use of TIB Docket-Book Data to construct an Annual Abundance Index for Torres Strait Rock Lobster – 2018 Update*

ix. Total effort (hours fished) – decrease in 2017/18 season compared to 2016/17 season.

x. Hours fished per tender day – increased markedly in 2017/18 season compared to 2016/17 season.

xi. Standardised CPUE – moon-phase was added to the model. CPUE is lowest during days near a full moon and also low around a new moon, while CPUE is highest mid-way between these two phases (i.e. around the first and last quarters). During these latter periods CPUE is around 30% higher than at the time of a full moon. Management controls have had an impact in the 2017/18 season. The standardised CPUE index indicates a below average season in 2017/18 but not much below and within normal range compared across previous seasons.

e. TIB sector catch and effort data from December 2017-July 2018:

i. Catch by method and process – the use of the hookah method in the 2017/18 season decreased corresponding with a decrease in whole (live) processed form.

ii. Catch by area fished – an industry member noted that a dinghy registered to Iama, but landing at Warraber, is likely to have taken the catch from around Iama or Warrior Reef. With this in mind the RAG agreed that future analyses conducted by CSIRO should explore the use of boat marks to conduct verification of location fished data provided in the TDB02 CDR. Discrepancies between boat marks and the location fished could be followed up with the individual fishers concerned.

**Action**

With regards to future TIB catch and effort analyses, CSIRO to explore the use of boat marks to improve location fished data extracted from the TDB02 CDR.

iii. Catch by days fished – there was an increase in the proportion of the catch associated with trips of length of greater than 1 day in the 2017/18 season, compared with previous seasons.

iv. Total effort (days fished) - the total number of days fished also increased in the 2017/18 season.

v. Nominal CPUE by month – December 2017 and January 2018 are lower than previous seasons.

vi. Nominal CPUE by method - catch rates for hookah use increased, and decreased for free diving in the 2017/18 season

vii. Nominal CPUE by area - catch rates were higher than average in the Mabuiag, Badu and Warrior areas.

viii. Standardised CPUE – as with the TVH model, moon-phase was added to the model. As with the TVH sector, the standardised CPUE index indicates a below average season in 2017/18 but not much below and within normal range compared across previous seasons. When comparing TIB and TVH indexes, the TVH index shows more inter-annual variability, but both sectors tend to be close to each other.

f. With regards to the standardisation of the CPUE:

i. It is assumed within each year that the pattern of fishing across each area remains relatively consistent over time. However, it is likely that with the introduction of new technologies (e.g. GPS) that, over time, fishers have been able to more precisely target their fishing effort.

ii. Continual increases in fishing power over time for individual vessels is not captured by the available data resulting in potential bias in the calculated indices of abundance.

iii. The area fished across the fishery has been decreasing over time, with the area fished reaching a minimum during the 2017/18 season. This suggests that the fishing effort was more aggregated during the 2017/18 season than in other seasons, but is uncertain because the location of fishing effort currently recorded in the logbook is the location of the primary vessel and not the associated tenders.

22. The RAG agreed improvements could be made in the collection of spatial (e.g. location, depth) and effort (e.g. hours in the water) data in both TVH and TIB logooks and CDRs. The RAG noted that should the TRL04 logbook or TDB02 CDR be changed, this will require analyses to deal with a break in the CPUE time-series across years. Some issues that need further investigation include:
    a. increases in fishing power in the Fishery through time and how to account for this in the CPUE standardisation (e.g. is ‘vessel-effect’ a proxy for skill of divers? Increase in boat size - can larger boats search more? Have there been other changes in fishing gears leading to increased CPUE?);
    b. what factors influence the spatial distribution of lobsters and hotspots, and what influences the spatial distribution of fishing effort;
    c. how fishing aggregations influence CPUE, and what factors influence aggregation dynamics;
    d. whether there is hyper-stability in the CPUE (based on factors above);
    e. the influence of oceanographic conditions (e.g. water temperature, prevailing winds).

# 5 Results of the 2018 mid-year survey

23. The RAG considered a presentation provided by Dr Timothy Skewes, scientific observer, detailing the results of the 2018 mid-year survey:
    a. The extent and number of surveys has changed over the years:
        i. 1989 benchmark survey - 542 sites, biomass estimate of 4,800 tonnes.
        ii. 2002 benchmark survey - 375 sites, biomass estimate of 1,100 tonnes.
        iii. 2004 biological and physical sampling by Pitcher et al 2007 looking at distribution of biota in the Torres Strait. Correlated with areas where TRL are known to be. Promising grounds out towards Deliverance, but this has not been surveyed.
        iv. 1990-2004 – mid-year surveys conducted.
        v. 2005-2008 – mid-year and pre-season surveys conducted with increased number of sites during the pre-season surveys.
        vi. 2009-2013 – mid-year surveys conducted.
        vii. 2014-2017 – pre-season surveys conducted.
        viii. 2018 - pre-season and mid-year surveys conducted
    b. 2018 mid-year survey - conducted between 28 June and 9 July. 73 sites from the pre-season survey were surveyed mid-year plus an additional 5 sites corresponding to hotspot areas in the north. Of these, site N109 was not surveyed. The weather and underwater conditions for the survey were generally good. There were some strong winds (20-25 knots) for the first 7-8 days, dropping to 15-20 knots over the last 3 days. The visibility was good, averaging 2.5-3m. The lowest recorded visibility was 1.5m.
    c. 2+ index of abundance - the 2+ abundance index from the 2018 mid-year survey is significantly lower than the previous eight mid-year survey indices and is the second lowest value on record. The 2018 index is 26% of the average survey indices over the period 1989-2004. The 2018 index falls within the confidence limits associated with the stock assessment model prediction, and is slightly lower than predicted.
    d. Additional 5 sites – the 2018 index for the Mabuiag stratum decreased slightly when adding the additional 5 sites. This could be partly because the lobsters were very spatially concentrated in this stratum and the survey has underestimated overall abundance because it is designed to provide a larger scale representative index. Alternatively, this suggests that the earlier hotspot concentrations of lobsters in this stratum have now been fished and the index is reflecting a lower abundance following the fishing pressure that has been exerted in this area. Industry members advised that the majority of hotspot sites had been harvested before being surveyed.

e. 1+ index of abundance - the 1+ recruiting abundance index is slightly higher than the upper 95% limit associated with the model prediction, and is seen to be at approximately the average historical value, suggesting that the 2018/19 fishing season will be improved relative to the 2017/18 fishing season.

f. Age class – there was an observed anomaly in the age class data where a significant proportion of the sampled lobsters fell between the average 1+ and 2+ age class ranges (i.e. meaning they were either larger 1+ lobsters or smaller 2+ lobsters). The RAG discussed a range of known factors that affects the growth of lobsters, including density dependence, water temperature, habitat and food availability. On the basis that water temperatures have been higher in more recent years, food availability has been high in the areas surveyed (e.g. good shell beds) and densities of lobsters have been lower, the best hypothesis to fit to this information is these lobsters are faster growing 1+ lobsters.

24. The RAG discussed industry concerns that what happened during the 2017/18 season was anomalous, in that industry have never been able to over-catch the TAC even when RBCs have been low in the past. The RAG noted an explanation from the Chair that low abundance does not necessarily mean that you can't catch the lobsters, particularly as it is known that TRL aggregate. It was further noted that the stock assessment model currently assumes there is a hyper-stable relationship between CPUE and biomass in this Fishery whereby fishers remain on fishing hotspots or move from one hotspot to another – thereby maintaining high catch rates that don't necessarily represent the population size of the entire stock.

25. The RAG discussed industry concerns over the decrease in the number of survey sites through time. The RAG noted that past analyses have shown that decreasing the number of sites will increase the standard error (decrease precision), however the trend of abundance remains the same.

# 6 Comparison of CPUE analyses against results for the 2017 pre-season and 2018 mid-year surveys

26. The RAG considered a presentation provided by Dr Éva Plagányi, CSIRO scientific member, comparing CPUE analyses against results for the 2017 pre-season and 2018 mid-year surveys:

a. Estimating stock abundance using surveys versus CPUE – surveys do not target areas (i.e. they are randomly stratified) whereas fishers do target and they generally become more efficient over time in doing so. This can lead to a hyper-stability effect which occurs in stocks that aggregate and/or where there are increases in fishing power (effort creep) through time. This means industry can maintain high CPUE even when a stock is declining. If these factors are not taken into account in CPUE analyses, then the CPUE may not provide a reliable index of abundance. Surveys are specifically designed to give a more reliable index of abundance due to their randomly stratified nature and broader coverage of a Fishery area. Survey abundance indices will never exactly match industry CPUE trends: some years it will over-estimate and some years it will under-estimate, but ***on average*** there is a strong correlation between survey and CPUE data (i.e. the trend is similar).

b. Relationship between CPUE and biomass in the Fishery – past modelling for the Fishery has shown that a non-linear regression line best fits the CPUE and mid-year 2+ data. This suggests that as stock abundance declines, CPUE is higher than what would be expected if there was a linear relationship or even accounting for hyper-stability. As a result of these past analyses, a hyper-stable relationship is assumed in the model (i.e. at low abundance, CPUE will be higher than true abundance). This assumption will be made clearer in future analyses. A further consideration is that if aggregation behaviour or fishing power changes from year-to-year, then the hyper-stable relationship will also change year-to-year, and may be able to explain some anomalous years. In summary, there is a hyper-stable relationship between CPUE and biomass in the Fishery, the stock in 2017/18 season was low and for various reasons outlined above, the CPUE data did not reflect this clearly. More accurate spatial and effort data would better inform CPUE analyses.

c. Connectivity of stocks – a study conducted by Dao et al 2015 looking at the dispersal of TRL found there is connectivity between the Torres Strait, PNG, Indonesia and the broader south-east Asian region. The study indicates that TRL could be recruiting to the Fishery from the west however, further work needs to be done to incorporate larval duration/settlement times into this study. A study conducted by Rothlisberg et al 1994 in the Gulf of Carpentaria did not find TRL in the Gulf itself but did sample a small number of TRL larvae to the north which could in theory recruit to the Torres Strait.

| **Action** |
| --- |
| Circulate copies of the Dao et al 2015 and Rothlisberg et al 1994 papers to the RAG for information. |

d. Environmental influences – there are a range of environmental factors that influence recruitment and abundance of TRL including water temperature, habitat changes and trawling impacts. A marine heatwave in February to April 2016 has been shown to have had direct impacts on fisheries across northern Australia. A resilient stock is needed to cope with these changes. This is part of the reason why, for every lobster taken in the Fishery, two need to be left behind.
e. Larval advection modelling – in normal years there is strong advection of TRL larvae into the Torres Strait whereas in El Nino years there is advection away from the Torres Strait. When modelling November 2015 through to March 2016 (this being the period of spawning for the 2018 2+ lobsters fished in the 2017/18 fishing season) an El Nino pattern is evident.
f. In summary, TRL is naturally variable, there were strong environmental influences in 2015/16, low stock abundance in 2017/18. CSIRO are sourcing funding to improve the environmental model for the Torres Strait to incorporate data on these environmental influences, including the complex tides in the region.

***CPUE data***

27. The RAG agreed that catch and effort data (and the indicators derived from these data e.g. CPUE) are fundamental to understanding the dynamics of the TRL stock and performance of the Fishery and agreed improvements that could be made to its collection and analysis, including:
    a. TRL04 logbook and TDB02 CDR - improving the accuracy of spatial data (e.g. point of capture as opposed to point of anchoring or landing), finer scale measure of effort (e.g. 'hours actively fishing/in the water' as opposed to 'days fished'), further details on effort (e.g. to include time spent travelling, searching and actively fishing), collection of depth data.
    b. Fishing power (efficiency) - developing a better understanding on changes in fishing behaviour and power over time (e.g. changes to the size of engines, use of GPS, gear, areas fished, time fished, experience of divers), to inform the standardisation of CPUE data.
    c. Use of data collection technology - assessing the use of electronic logbooks in the Fishery.
    d. Use of monitoring technology - assessing the use of a vessel monitoring system (VMS) on all boats in the Fishery.
    e. PNG catch and effort data – better understanding of PNG catch and effort inside and outside of the TSPZ including spatial and temporal data.
28. The RAG agreed a sub-group of the RAG be formed to progress these issues. Nominations to form the sub-group were received from the following members: Selina Stoute; Danielle Stewart; Dr Éva Plagányi; Dr Andrew Penney; Mark David; Les Scott; and Joseph Posu. Trent Butcher and Suzannah Salam also offered their nominations as observers at the meeting. Membership of the sub-group is to be finalised out-of-session. A draft terms of reference is also to be developed for consideration at the first meeting of the sub-group to be convened alongside the next meeting of the RAG.

**Recommendation**

The RAG recommended a sub-group of the RAG be established to examine and recommend improvements to be made to the collection and analysis of catch and effort data for the TRL Fishery, including:

a. TRL04 logbook and TDB02 CDR - improving the accuracy of spatial data (e.g. point of capture as opposed to point of anchoring or landing), finer scale measure of effort (e.g. 'hours actively fishing/in the water' as opposed to 'days fished'), further details on effort (e.g. to include time spent travelling, searching and actively fishing), collection of depth data.
b. Fishing power (efficiency) - developing a better understanding on changes in fishing behaviour and power over time (e.g. changes to the size of engines, use of GPS, gear, areas fished, time fished, experience of divers), to inform the standardisation of CPUE data.
c. Use of data collection technology - assessing the use of electronic logbooks in the Fishery.
d. Use of monitoring technology - assessing the use of VMS on all boats in the Fishery.

The RAG further recommended a draft terms of reference is to be developed for consideration at the first meeting of the sub-group to be convened alongside the next meeting of the RAG.

29. The RAG discussed that these improvements will enable further analyses to better understand the CPUE-biomass relationship for the Fishery and the environmental influences affecting recruitment and TRL stock abundance. These are issues that can be examined in further detail by the sub-group at a later time.
30. Noting improved catch sharing during the 2017/18 fishing season, the RAG agreed that AFMA should continue to work closely with PNG to improve data sharing arrangements between the two jurisdictions.

***TRL Fishery Harvest Strategy***

31. The RAG discussed the implications of the analyses presented at the meeting for the draft Harvest Strategy for the Fishery. The RAG discussed the empirical HCR (eHCR) that will be used to calculate the RBC, once the draft Harvest Strategy is adopted, uses the pre-season survey 1+ and 0+ indices, both standardised CPUE indices (TVH and TIB), applies the natural logarithms of the slopes of the five most recent years' data and includes an upper catch limit of 1,000 tonnes. The relative weightings of the eHCR indices are 70% pre-season survey 1+ index, 10% pre-season survey 0+ index, 10% TIB sector standardised CPUE and 10% TVH sector standardised CPUE. The five year index average was selected by the RAG to limit the variability of the RBC from year to year.
32. The RAG also discussed the decision rules contained in the draft Harvest Strategy that trigger a stock assessment and mid-year survey. The draft Harvest strategy details that if in any year the pre-season survey 1+ indices is 1.25 or lower (average number of 1+ age lobsters per survey transect) it triggers a stock assessment. If the eHCR limit reference point is triggered in the first year, a stock assessment update must be conducted in March. If after the first year the stock is assessed below the biomass limit reference point, it is optional to conduct a mid-year survey, the pre-season survey must continue annually. The RAG discussed that given the experience during the 2017/18 season, the mid-year survey trigger may not align with the current expectations of management or industry.
33. The RAG noted advice from the CSIRO scientific member, that these issues do not affect the management strategy evaluation (MSE) testing that has already been done in developing the draft Harvest Strategy, and this testing can be drawn on to further examine these two issues.
34. The RAG agreed that these two issues should be revisited at the next meeting of the RAG prior to finalising the Harvest Strategy.

**Recommendation**

In light of the 2017/18 season, the RAG recommended that the number of years in the eHCR index and decision rule triggers be revisited at the next meeting of the RAG prior to finalising the Harvest Strategy.

***TRL Fishery Surveys***

35. The RAG discussed survey options to support future stock assessments and management of the TRL Fishery. CSIRO declared their conflicts of interest in discussions on this item:
    a. Benchmark survey – this option would cost $486,000 (CSIRO contribution $194,000, external contribution $291,000). This would build on previous benchmark surveys conducted in 1989 and 2002. Although it would improve the precision of the pre-season survey indexes of abundance for the 2018/19 season and future seasons, past analyses have shown that while increasing the number of sites (e.g. from 73 to 146) will decrease the standard error (increase precision), the trend of abundance remains basically the same, although the likelihood of having an outlier is lower. The RAG noted the benchmark survey could be redesigned to examine specific issues, such as if the survey and fishing footprints don't align or if it is suspected that there has been a shift in the distribution of the TRL stock. However, this would require lead time and cannot be done before the 2018/19 season. An independent review would provide a good basis for assessing the merits of a benchmark survey.
    b. Additional sites surveyed in 2018 pre-season survey – the CSIRO scientific member noted that as a contract has already been signed with the charter company for the 2018 pre-season survey, CSIRO are constrained in what changes can be made to the survey design (e.g. number of additional sites). The RAG noted that the survey could accommodate an additional 6 sites if required. The RAG agreed that selecting additional sites to target hotspots would not be effective, as the spatial and temporal distribution of aggregations is not well understood and they are likely to vary/move from year to year in ways that cannot currently be predicted.
    c. Independent review of survey design – the AFMA member noted that peer review of scientific methods, both that done by RAGs and externally, is an essential element in the fisheries management process. RAGs should view external, independent peer review as an essential component of their business. The CSIRO scientific member welcomed an independent review of the survey design, noting it would require resources from CSIRO to draw together the documentation need to support the review. The member further noted that another university had recently reviewed the survey design and agreed to provide a copy of the report to the RAG for information. The RAG agreed that an independent review should be forward looking and provide an independent assessment of issues encountered in the 2017/18 season and improvements that can be made to the survey methodology.

| **Action** |
| --- |
| CSIRO to provide information on a recent review of the survey design to the RAG for information. |

36. The RAG agreed that improvements to the catch and effort data would add value to CPUE as an index of TRL stock status and performance of the Fishery.
37. Taking into account budgeting and time constraints, the RAG agreed to a staged approach to addressing the issues raised above:
    a. November 2018 pre-season survey to be conducted with the addition of the further 6 sites in the north (as per the mid-year survey);
    b. independent review to be conducted of the survey design. A draft terms of reference is to be developed by the Chair for consideration at the first RAG meeting in 2019. Pending further input by the RAG, the review should examine the following:
        i. pre-season survey methodology;
        ii. merits of alternative survey approaches (e.g. benchmark and mid-year surveys);
        iii. CPUE vs. survey mismatch and hyper-stability in CPUE;
        iv. availability and merits of alternative data collection technologies.

**Recommendation**

The RAG recommended:

a. the 2018 pre-season survey be conducted with the addition of a further 6 sites.

b. an independent review to be conducted of the survey design. A draft terms of reference is to be developed by the Chair for consideration at the first RAG meeting in 2019.

# 7 Planning and design of future surveys and assessments

38. The RAG considered a presentation provided by Dr Timothy Skewes, scientific observer, detailing the plan for the 2018 pre-season survey. The 2018 pre-season survey will be conducted from 11-24 November 2018 and will survey 80 sites.
39. The RAG discussed the use of industry vessels to conduct future surveys, noting CSIRO charter requirements (**Attachment D**). An industry member noted that they would be able to meet the requirements detailed.
40. The RAG noted a poster presented by CSIRO showing the TRL age classes. The RAG agreed to provide comments out-of-session, prior to finalisation.

**Action**

RAG members to provide comments on the CSIRO TRL age class poster.

CSIRO to include a better image of the 2+ lobster on the poster

# 8 Better aligning the TAC setting process with the fishing season for the 2018/19 season and future seasons

41. The RAG discussed approaches to better aligning the current TAC setting process with the fishing season, noting the timing of the survey and stock assessment process means a TAC based on the latest survey results cannot be determined before the current season start date (1 December). Currently, the notional TAC has not been finalised until 4-5 months into the 10 month fishing season. Under the proposed Management Plan a TAC must be determined before the season start.
42. The RAG discussed two approaches:
    a. <u>Delayed season start</u> - delaying the fishing season start date so that it occurs after the TAC setting process is able to be finalised (e.g. 1 February, 1 March). This may require timeframes for some components of the TAC setting process to be completed earlier or compressed.
    b. <u>Interim conservative TAC</u> - setting a conservative TAC that could be determined before the start of the season and increased when the TAC setting process is finalised. The conservative TAC would need to be determined before the results of the pre-season survey become available in December.
43. The RAG considered that although it will be possible to finalise a RBC more quickly through the application of the eHCR once the Harvest Strategy is finalised, administratively, a TAC would still not be finalised by 1 December. Further, the draft Harvest Strategy requires annual RBCs to be set using the integrated stock assessment model if the if the data, analyses or other conditions indicates the eHCR recommended RBCs are outside the ranges tested by the MSE process conducted. Under this scenario the eHCR should be revised and annual RBCs need to be set using the integrated stock assessment model until a revised eHCR is agreed.
44. With regard to delaying the fishing season start date, the RAG discussed the following considerations:
    a. <u>Inputs to the eHCR</u> – the eHCR uses the pre-season survey 1+ and 0+ indices and both standardised CPUE indices (TVH and TIB) to calculate the RBC. CPUE data would be needed to the end of September. It usually takes until the end of October to chase up outstanding records and compile the data ready for analysis. CSIRO then conduct the

analyses and prepare the standardised CPUE indices in November. The pre-season survey is generally conducted between 5-20 November each year. At least two weeks are needed following the survey to compile and analyse the survey data and run the eHCR calculations.

b. Administrative decision making – the recommended RBC needs to be considered by the RAG and Working Group before the PZJA is asked to make a decision. The PZJA process can take up to 3 months, however, AFMA is working to streamline PZJA decision making processes to enable more timely decision making. The RBC and associated catch shares also need to be agreed with PNG.

45. Noting the above constraints, the RAG considered the conservative TAC approach a more viable approach. The RAG noted that other fisheries have adopted this approach and it can work well if formulated correctly. This approach will still require timeframes for some components of the TAC setting process to be completed earlier or compressed. The RAG discussed a range of options for setting a conservative TAC, to be described as the start of season catch limit:

a. Constant catch limit – in developing the draft Harvest Strategy, MSE testing was conducted on a HCR whereby a constant TAC was set from year-to-year. The testing showed that 360 tonnes is a safe level to set the TAC in such a scenario. The RAG noted that this testing only showed that this is a safe level if it is set over a number of years, not in the context of a variable TAC.

b. Cumulative catch from December-February – the RAG noted the following cumulative catches for December-February for the period 2005-2018.

| | December-February Total (kg) | December-March Total (kg) |
|---|---|---|
| Maximum | 201,715 | 366,212 |
| Minimum | 57,441 | 99,425 |
| Mean (average across years) | 93,723 | 165,292 |

c. Start of season catch limit – the RAG agreed that the start of season catch limit should cover 1 December through to the end of February, and be based on the maximum annual catch amount for the period 2005-2018, being 200 tonnes. This is to minimise the risk that the limit could artificially constrain fishing effort, particularly in a good year. The RAG noted that the use of hookah gear is not permitted during December-January.

d. PNG catch – the RAG further agreed that, if needed, an additional 100 tonnes be added to the start of season catch limit amount, to account for catches from PNG.

e. Exceptional circumstances – the RAG agreed the start of season catch limit should be overridden in seasons where the TRL stock abundance is exceptionally low and the final RBC is likely to fall below the start of season catch limit or where overridden by the Harvest Strategy decision rules. In such cases, the use of the start of season catch limit should not be used in subsequent seasons until reviewed by the RAG.

**Recommendation**

Considering the need under the proposed Management Plan to determine a TAC prior to the start of the fishing season on 1 December, and noting that current stock assessment and decision making processes do not enable a TAC to be determined until the end of February, the RAG recommended that once the Management Plan comes into force:

a. a start of season catch limit of 200 tonnes be determined prior to 1 December each year covering the period 1 December through to the end of February, at which point a final TAC will be able to be determined; and

b. a provision for the start of season catch limit to be overridden in seasons where the TRL stock abundance is exceptionally low and the final RBC is likely to fall below the start of season catch limit or where overridden by the Harvest Strategy decision rules. In such cases, the use of the start of season catch limit should not be used in subsequent seasons until reviewed by the RAG.

46. An industry observer advised that, considering the limits that were applied during the 2017/18 fishing season, the concept of a start of season catch limit could be confusing for, or misconstrued by industry if not communicated clearly. AFMA agreed to prepare some explanatory material and a diagram for members to use in any discussion they may have with industry.

| **Action** |
| --- |
| AFMA to prepare some explanatory material and a diagram explaining the start of season catch limit. |

# 9 Draft five-year research plan for 2019/20 to 2022/23

47. The RAG considered an update provided by the Executive Officer concerning the new research planning framework for Torres Strait fisheries:
    a. over the past 12 months, AFMA and the Torres Strait Scientific Advisory Committee (TSSAC) have been drafting a new Strategic Research Plan (SRP) for Torres Strait research. The SRP is an overarching document which details TSSAC's strategic themes which will guide priority setting for research in the Torres Strait fisheries over the next five years.
    b. TSSAC now requires each fishery to develop a rolling five year research plan, which fits into the themes identified in this SRP. The plans are written by the relevant Torres Strait forum (Working group, MAC or RAG). These plans will then be used by TSSAC to create an annual research statement (ARS), listing annual priorities for Torres Strait research across all fisheries. The rolling five year research plans will be updated annually, thus always having a five year projection for research.
48. The RAG discussed the draft Rolling Five Year Research Plan for 2019/20-2022/23 for the Torres Strait Tropical Rock Lobster (TRL) Fishery and recommended changes as detailed in **Attachment E**.

# 10 Other business

49. Members did not raise any other business for consideration.

# 11 Date and venue for next meeting

50. The RAG noted that the next meeting is scheduled for 11-12 December 2018 for the purpose of discussing the preliminary results of the 2018 pre-season survey and stock assessment.
51. The meeting was closed in prayer at 11:30 am on 19 October 2018.

**Declaration of interests**
**Dr Ian Knuckey – October 2018**

**Positions:**

| | |
|---|---|
| Director – | Fishwell Consulting Pty Ltd |
| Director – | Olrac Australia (Electronic logbooks) |
| Deputy Chair – | Victorian Marine and Coastal Council |
| Chair / Director – | Australian Seafood Co-products & ASCo Fertilisers (seafood waste) |
| Chair – | Northern Prawn Fishery Resource Assessment Group |
| Chair – | Tropical Rock Lobster Resource Assessment Group |
| Chair – | Victorian Rock Lobster and Giant Crab Assessment Group |
| Scientific Member – | Northern Prawn Management Advisory Committee |
| Scientific Member – | SESSF Shark Resource Assessment Group |
| Scientific Member – | Great Australian Bight Resource Assessment Group |
| Scientific Member – | Gulf of St Vincents Prawn Fishery Management Advisory Committee |
| Scientific participant – | SEMAC, SERAG |

**Current projects:**

| | |
|---|---|
| AFMA 2018/08 | Bass Strait Scallop Fishery Survey – 2018 and 2019 |
| FRDC 2017/069 | Indigenous Capacity Building |
| FRDC 2017/122 | Review of fishery resource access and allocation arrangements |
| FRDC 2016/146 | Understanding declining indicators in the SESSF |
| FRDC 2016/116 | 5-year RD&E Plan for NT fisheries and aquaculture |
| AFMA 2017/0807 | Great Australian Bight Trawl Survey – 2018 |
| Traffic Project | Shark Product Traceability |
| FRDC 2018/077 | Implementation Workshop re declining indicators in the SESSF |
| FRDC 2018/021 | Development and evaluation of SESSF multi-species harvest strategies |
| AFMA 2017/0803 | Analysis of Shark Fishery E-Monitoring data |
| AFMA 2016/0809 | Improved targeting of arrow squid |

**24th MEETING OF THE PZJA TORRES STRAIT TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG 24)**

**Thursday 18 October 2018 (8:00 AM – 4:00 PM)**
**Friday 19 October 2018 (8:00 AM – 12:00 PM)**

**Cairns (Northern Fisheries Centre, 38-40 Tingira Street, Portsmith)**

# DRAFT AGENDA

**1 Preliminaries**

1.1 Welcome and apologies

1.2 Adoption of agenda

1.3 Declaration of interests

1.4 Action items from previous meetings

1.5 Out-of-session correspondence

**2 Updates from members**

2.1 Industry and scientific members

2.2 Government agencies

2.3 PNG National Fisheries Authority

2.4 Native Title

**3 Catch summary for the 2017/18 fishing season**

**Presentation from Dr Andrew Penney**

**4 Catch and CPUE analyses for the 2017/18 fishing season**

**5 Results of the 2018 mid-year survey**

**6 Comparison of CPUE analyses against results of the 2017 pre-season and 2018 mid-year surveys**

**7 Planning and design of future surveys and assessments**

**8 Better aligning the TAC setting process with the fishing season for the 2018/19 season and future seasons**

**9 Draft five-year research plan for 2019/20 to 2022/23**

**10 Other business**

**11 Date and venue for next meeting**

**Action items from previous TRLRAG meetings**

| # | Action Item | Agenda | Agency | Due Date | Status |
|---|---|---|---|---|---|
| 1. | AFMA to review the effectiveness of certain TIB licensing arrangements (in its 2016 licencing review) including:<br>• TIB licenses should share a common expiry date<br>• licences to last for longer than the current 12 month period. | TRLRAG14 (25-26 August 2015) | AFMA | 2017 | **Ongoing**<br>AFMA has begun undertaking a review of licensing of Torres Strait Fisheries, this issue will be considered as part of this review. At present however, AFMA resources are focused on progressing the proposed legislative amendments as a matter of priority.<br>• Administrative arrangements can be made to provide for licences held by the same person to expire on the same day. This change can be progressed when resources allow.<br>• The *Torres Strait Fisheries Regulations 1985* currently provide for TIB and TVH licences to be issued for up to 5 years. Administrative arrangements can be progressed when resources allow. |
| 2. | AFMA and CSIRO prepare a timeline of key events that have occurred in the Torres Strait Tropical Rock Lobster Fishery (e.g. licence buy backs, weather events and regulation changes) and provide a paper to TRLRAG. | TRLRAG14 (25-26 August 2015) | AFMA<br>CSIRO | TRLRAG17 (31 March 2016) | **Ongoing**<br>AFMA to complete further work. This has been difficult to action ahead of other priorities for the TRL Fishery. |
| 3. | AFMA to prepare a summary of evidence that PNG trawl-caught TRL are a shared stock between Australia and PNG, including details such as the TRL biological characteristics, larvae dispersal, tag recapture data and catch and effort information. AFMA will circulate the paper to the RAG out-of-session for | TRLRAG19 (13 December 2016) | AFMA | | **Completed**<br>AFMA sent a letter to PNG NFA outlining concerns of trawlers retaining TRL on 8 March 2017.<br>At TRLRAG 21 held from 12-13 December 2017, CSIRO presented the preliminary results of the research project titled '*Environmental update for the Torres Strait tropical lobster Panulirus ornatus*'.<br>AFMA presented the key findings of the CSIRO larval advection model at the Fisheries Bilateral meeting held in Port Moresby on 5 February 2018. The bilateral meeting |

| # | Action Item | Agenda | Agency | Due Date | Status |
|---|---|---|---|---|---|
| | comment before sending to PNG NFA. | | | | noted that the findings show the Australian and PNG TRL fisheries are based on a single stock.<br>AFMA and CSIRO (Dr Éva Plagányi) met with PNG NFA officials, including the NFA Managing Director, John Kasu on 7 February 2018 at the NFA offices in Port Moresby. Dr Plagányi presented the updated stock assessment results and larval advection modelling. There was agreement that the updated larval modelling together with past research provides strong evidence that TRL is a shared stock between Australia and PNG.<br>These meetings have been followed up with teleconference between the PNG NFA Managing Director and AFMA CEO which included discussions on the importance of controlling catches so they do not exceed each jurisdiction's catch share of the recommended biological catch (RBC).<br>CSIRO's final report, titled '*Environmental Drivers of variability and climate projections for Torres Strait tropical lobster Panulirus ornatus'*, will be provided with these meeting papers for reference. This report has not been sent to members previously. This report will also be made available on the PZJA website. |
| 4. | Malu Lamar RNTBC to provide AFMA with the map of traditional boundaries and regional area and reef names for each of the Torres Strait Island nations and for CSIRO to examine possible revised naming conventions for survey sites | TRLRAG20 (4-5 April 2017) | Malu Lamar | | **Completed**<br>CSIRO advised at TRLRAG23 that they have received some maps with information on traditional names but that this is not complete. CSIRO will work with Malu Lamar if further information is needed. |
| 5. | AFMA to liaise with Mr Pitt and Malu Lamar to provide agreed traditional names for the area around Erub. | TRLRAG23 (15 May 2018) | AFMA | | **Ongoing** |

| # | Action Item | Agenda | Agency | Due Date | Status |
|---|---|---|---|---|---|
| 6. | Dr Campbell's corrected paper to be circulated to the RAG following the meeting. | TRLRAG23 (15 May 2018) | CSIRO | TRLRAG24 (18-19 October 2018) | **Completed**<br>Updated paper provided to TRLRAG members on 16 May 2018. |
| 7. | South Fly River studies to be provided for consideration at the next TRL and Finfish RAG meetings. | TRLRAG23 (15 May 2018) | AFMA | TRLRAG24 (18-19 October 2018) | **Ongoing**<br>To be provided out of session and for consideration at the next RAG and WG meetings if required. |

**Relevant action items from previous TRLWG meetings***

| # | Action Item | Agenda | Agency | Due Date | Status |
|---|---|---|---|---|---|
| 1 | TRLRAG to provide advice on any findings relating to the impacts of changing the season start date to provide industry with a longer TAC notice period. | TRLWG5 (5-6 April 2016) | AFMA to draft RAG paper | TRLRAG22 (27-28 March 2018) | **Ongoing**<br>To be discussed under Agenda Item 8. |

*TRLWG actions not relevant to TRLRAG have not been included in the above.

## CSIRO charter requirements for TRL survey

### Mandatory Requirements

- Charter vessel greater than 16m and surveyed as a 1B or 2B class vessel
- Tenderer must meet all legislative and regulatory requirements for sea worthiness for Marine Safety (Domestic Commercial Vessel) National Law Act 2012 and associated Marine Orders
- Capacity to accommodate 4 CSIRO staff and 2 charter vessel crew
- Be available for a period of 14 days charter during November neap tides (up to 80 dive sites)
- Protection and Indemnity Insurance and WorkCover for Tenderer's employees

### Goods and Services to supply

- Charter crew are required to have Advanced Resuscitation Certification or similar which includes oxygen therapy
- Provide all meals, linen and accommodation for 4 CSIRO staff
- Provide enough fresh water for adequate drinking, showering (6 persons), washing of clothes and dive equipment for the survey period
- Have an emergency plan for evacuation from the survey region in case of medical emergency, particularly related to diving incidents
- Provide and operate dive compressor with recent air test certificate (within the last 6 months)
- Capacity to stow away approximately 2.5 cubic meters of survey equipment (wt. 300kg)
- Tenderer to supply the following equipment
    - 400L unleaded fuel and 10L 2 stroke outboard oil
    - dive tanks with A-clamp fittings (in test)
    - 20 x 1.5kg dive weights
    - F-size oxygen tank and Oxy-Viva kit (in service) for therapy in case of medical emergency.

**Action items from previous TRLRAG meetings**

| # | Action Item | Meeting | Responsible Agency/ies | Due Date | Status |
|---|---|---|---|---|---|
| 1. | AFMA to review the effectiveness of certain TIB licensing arrangements (in its 2016 licencing review) including:<br>• TIB licenses should share a common expiry date<br>• licences to last for longer than the current 12 month period. | TRLRAG14 (25-26 August 2015) | AFMA | 2017 | **Ongoing**<br>AFMA has begun undertaking a review of licensing of Torres Strait Fisheries, this issue will be considered as part of this review. At present however, AFMA resources are focused on progressing the proposed legislative amendments as a matter of priority. Further work on this item will be progressed in the 2019/20 financial year.<br>• Administrative arrangements can be made to provide for licences held by the same person to expire on the same day. This change can be progressed when resources allow.<br>• The *Torres Strait Fisheries Regulations 1985* currently provide for TIB and TVH licences to be issued for up to 5 years. Administrative arrangements can be progressed when resources allow. |
| 2. | AFMA and CSIRO prepare a timeline of key events that have occurred in the Torres Strait Tropical Rock Lobster Fishery (e.g. licence buy backs, weather events and regulation changes) and provide a paper to TRLRAG. | TRLRAG14 (25-26 August 2015) | AFMA<br>CSIRO | TRLRAG17 (31 March 2016) | **Ongoing**<br>AFMA to complete further work. This has been difficult to action ahead of other priorities for the TRL Fishery. |
| 3. | AFMA to liaise with Mr Pitt and Malu Lamar to provide agreed traditional names for the area around Erub. | TRLRAG23 (15 May 2018) | AFMA | | **Ongoing**<br>Further discussions needed to finalise this action. A map developed by the TSRA's Land and Sea Management Unit in consultation with PBCs, has recently been developed. A copy of this map has been provided to |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | CSIRO and is provided at **Attachment 1.4c** for information. |
| 4. | South Fly River studies to be provided for consideration at the next TRL and Finfish RAG meetings. | TRLRAG23 (15 May 2018) | AFMA | TRLRAG24 (18-19 October 2018) | **Ongoing**<br>A report detailing the findings of these studies is currently being finalised and will be provided once available, expected just prior to TRLRAG25. |
| 5. | With regards to future TIB catch and effort analyses, CSIRO to explore the use of boat marks to improve location fished data extracted from the TDB02 CDR. | TRLRAG24 (18-19 October 2018) | CSIRO | 2019 | **Ongoing**<br>To be examined when the next analyses are undertaken. |
| 6. | Circulate copies of the Dao et al 2015 and Rothlisberg et al 1994 papers to the RAG for information. | TRLRAG24 (18-19 October 2018) | AFMA | TRLRAG25 | **Completed**<br>Papers provided at **Attachments 1.4d-e** for information. |
| 7. | CSIRO to provide information on a recent review of the survey design to the RAG for information. | TRLRAG24 (18-19 October 2018) | CSIRO | TRLRAG25 | **Ongoing**<br>A review of the Torres Strait TRL Fishery survey design by the U.S. National Park Service is not yet finalised for distribution. A copy will be provided to the RAG once finalised. Provided at **Attachments 1.4f-i** for information are published peer-reviewed papers relating to the Torres Strait TRL Fishery survey design. |
| 8. | RAG members to provide comments on the CSIRO TRL age class poster.<br>CSIRO to include a better image of the 2+ lobster on the poster | TRLRAG24 (18-19 October 2018) | RAG<br>CSIRO | 2019 | **Ongoing**<br>Comments to be provided out-of-session and poster to be finalised in 2019. |
| 9. | AFMA to prepare some explanatory material and a diagram explaining the start of season catch limit. | TRLRAG24 (18-19 October 2018) | AFMA | TRLRAG25 | **Completed**<br>Diagram provided at **Attachment 1.4j** developed and distributed to interested stakeholders. Further explanation |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | was provided to all TRL Fishery licence holders prior to the start of the 2018/19 fishing season. |

**Relevant action items from previous TRLWG meetings***

| # | Action Item | Meeting | Responsible Agency/ies | Due Date | Status |
|---|---|---|---|---|---|
| 1. | Discard reporting and estimation be considered by the RAG (possibly by the RAG data subgroup) | TRLWG8 (8 November 2018) | AFMA<br>RAG | 2019 | **Not complete**<br>RAG data sub-group yet to convene. Sub-group to be convened alongside the next meeting of the RAG in 2019. |
| 2. | RAG to consider the merit and options for improving the index of 0+ lobster abundance, through logbooks or other means. The Working Group noted that this would may be relevant to the RAG data sub-committee. | TRLWG8 (8 November 2018) | AFMA<br>RAG | 2019 | **Not complete**<br>RAG data sub-group yet to convene. Sub-group to be convened alongside the next meeting of the RAG in 2019. |

*TRLWG actions not relevant to TRLRAG have not been included in the above.

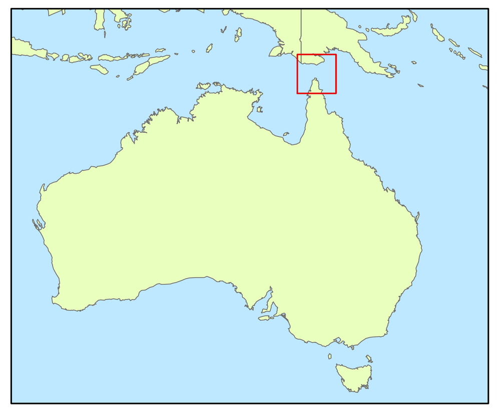

# LEGISLATIVE BOUNDARIES AND AREAS OF SIGNIFICANCE IN THE TORRES STRAIT

Abstract: The Torres Strait Region is extremely complex with many different jurisdictional and legislative boundaries overlapping in an area of high environmental and cultural value. The purpose of this map is to display some of the significant boundaries and areas that exist in the region with an accurate representation of the reefs and island systems that make up the Torres Strait. Island and reef names in the Torres Strait can vary between different language groups. This map has used traditional names where available. Western names for islands and reefs have been used in brackets or where no traditional name was known. The Author recognises that there may be discrepancy over the names and spelling however the best available information at the time of map production has been used.

- PNG Treaty Villages
- Weather Station
- Warraberalgal Porumalgal IPA
- GBRMP Boundary
- Shipping Channel
- Fisheries Jurisdiction Line
- Seabed Jurisdiction Line
- Protected Zone Boundary
- Dugong Sanctuary Extention
- Declared IPA
- Dugong Sanctuary
- Native Title Sea Claim Area
- Reefs and Shoals
- Land Mass
- Ocean

N S E W

0 20 40
Kilometres



Produced on 11/04/2014
Updated on 30/09/2014
Produced by M.S.
TRC: PM 2014 002

Coordinate System: GCS GDA 1994
Datum: GDA 1994
Units: Degree



Acknowledgments: This map incorporates data which is -
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Australian Government

TSRA
www.tsra.gov.au

RESEARCH ARTICLE

# Oceanographic Currents and Local Ecological Knowledge Indicate, and Genetics Does Not Refute, a Contemporary Pattern of Larval Dispersal for The Ornate Spiny Lobster, *Panulirus ornatus* in the South-East Asian Archipelago

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OPEN ACCESS

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## Abstract

Here we utilize a combination of genetic data, oceanographic data, and local ecological knowledge to assess connectivity patterns of the ornate spiny lobster *Panulirus ornatus* (Fabricius, 1798) in the South-East Asian archipelago from Vietnam to Australia. Partial mitochondrial DNA control region and 10 polymorphic microsatellites did not detect genetic structure of 216 wild *P. ornatus* samples from Australia, Indonesia and Vietnam. Analyses show no evidence for genetic differentiation among populations (mtDNA control region sequences $\Phi_{ST}$ = -0.008; microsatellite loci $F_{ST}$ = 0.003). A lack of evidence for regional or localized mtDNA haplotype clusters, or geographic clusters of microsatellite genotypes, reveals a pattern of high gene flow in *P. ornatus*throughout the South-East Asian Archipelago. This lack of genetic structure may be due to the oceanography-driven connectivity of the pelagic lobster larvae between spawning grounds in Papua New Guinea, the Philippines and, possibly, Indonesia. The connectivity cycle necessitates three generations. The lack of genetic structure of *P. ornatus*population in the South-East Asian archipelago has important implications for the sustainable management of this lobster in that the species within the region needs to be managed as one genetic stock.

## Introduction

The ornate spiny lobster, *Panulirus ornatus*, lives in tropical waters of the Indo-West Pacific from the Red Sea and south-east Africa in the west to Japan and Fiji in the east.The species is of

**Competing Interests:** The authors have declared that no competing interests exist.

significant commercial importance supporting local capture fisheries and developing aquaculture operations. *P.ornatus* pueruli (final lobster larval stage) are heavily exploited as seed-stock for aquaculture in South-East Asia, particularly in Vietnam and Indonesia, where wild pueruli are collected from the ocean in large numbers [1]. Even though natural fluctuations on larval recruitment are common to other spiny lobsters [2–4], there is concern from fishery managers that large fluctuations in juvenile recruitment and puerulus settlement repeatedly experienced in recent years represent a high risk to the adult lobster fishery [5, 6]. This apprehension was highlighted in 2006–2007 and 2009–2010, when the *P. ornatus* pueruli wild harvest in Vietnam was only ~50% of that caught in other years [1, 7]. This high variability in pueruli settlement raised concerns as to whether the annual removal of 1–2 million pueruli by fishers in Vietnam was significantly impacting the demography of the species, particularly that of adult populations. However, very little is understood about the population distribution and dynamics of *P. ornatus* and it is not known where the source of pueruli being harvested is situated. An investigation into the connectivity among spiny lobster populations is therefore needed to provide data on the resilience and sustainability of heavy exploitation, as well as to provide information on larvae sources and sinks.

Several approaches are available to evaluate connectivity between marine populations, including genetic markers (e.g. mitochondrial DNA or microsatellites), geochemical markers (e.g. microchemical signatures in shells), and/or the utilization of high-resolution biophysical models; however none of these approaches are likely to be conclusive in isolation and have not yet been applied to adequately address population connectivity in *P. ornatus* [8–10]. To date the studies that have been done have been limited to hydrodynamic-dispersion models of *P. ornatus* in restricted areas of the species distribution. Previous studies in eastern Australian waters [11] and in the Philippines [12] focused on short-term larval dispersion within a single generation of *P. ornatus* (i.e. from spawning ground to puerulus settlement site over a few months). According to these models most larvae released from spawning grounds in the Coral Sea, such as the Gulf of Papua, would be carried back to the coastline of northeast Queensland, while a part of them could advect northward to the Vitiaz Strait of eastern PNG within three months [11]. From different spawning grounds in both western and eastern coasts of the Philippines, larvae would be transported northward to Taiwan, advected into the South China Sea, or dispersed into the interior of the Sulawesi Sea [12]. These studies, however, could not address the issue of connectivity of *P. ornatus* across the broader South-East Asian archipelago (Fig 1).

The bathymetry and oceanography of the South-East Asian archipelago is very complex, with numerous shoals, straits, islands, reefs, and semi-enclosed seas, as well as mass-flow of water carried by currents between the Pacific and Indian Oceans. Currently there is no fine-scale oceanographic model encompassing the whole archipelago to assist in better understanding the drivers influencing *P. ornatus* genetic structure, or in fact connectivity of other marine species. The existing oceanographic models include a number of fine-scale models focusing on restricted areas within the archipelago (e.g. [13]), and medium-scale models of the whole domain (e.g. [14]) that have a grid size too coarse to resolve the current fluxes through the Philippines Straits and, as a result, they largely ignore the connectivity between the Philippine Sea, the South China Sea and the western Pacific Ocean [15].

Adults *P. ornatus* are found in waters from 1 to 50m in depth and occupy diverse habitats such as sandy and muddy substrates, coral reefs, rocky bottoms and even turbid coastal waters [16]. Adults are known to migrate by walking along the seafloor for hundreds of kilometers to form large spawning aggregations; for instance, adult *P. ornatus* from the Torres Strait, Australia, migrate up to 500 km to a spawning ground near Yule Island in the Gulf of Papua [17–19]. Furthermore, *P. ornatus* larvae have a long planktonic phase lasting between 135 to 210 days

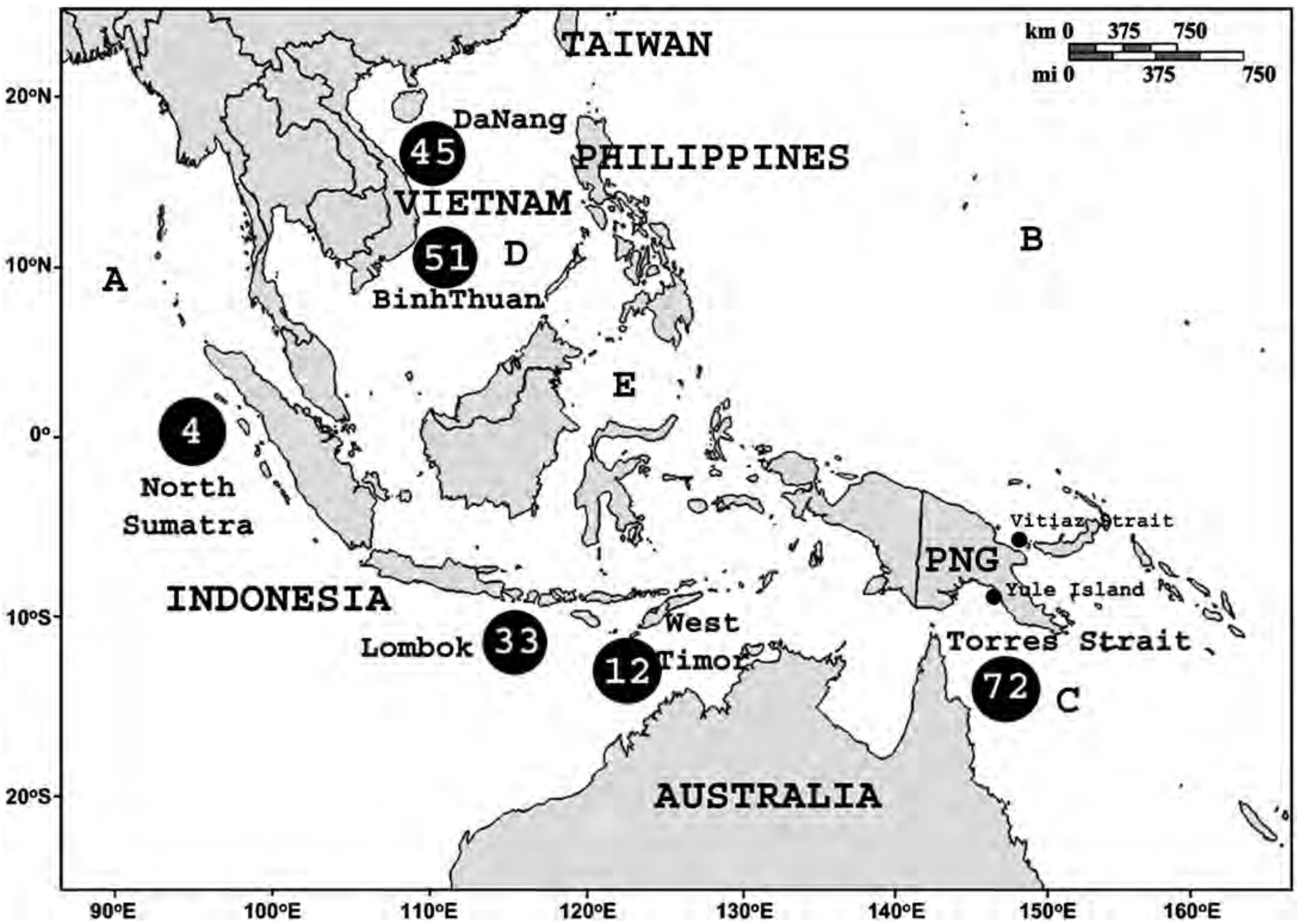


**Fig 1. Sampling sites and number of *Panulirus ornatus* specimens collected from across the tropical waters of the South-East Asian archipelago.** The numbers of individuals sampled at each location are indicated within the black circles. A Indian Ocean. B Pacific Ocean. C Coral Sea. D South China Sea. E Sulawesi Sea.

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[17, 20]. Before settlement the larvae metamorphose to the puerulus stage, which is the final larval stage with strong swimming ability; this phase lasts 9–25 days in the laboratory and possibly more in nature [4, 17]. Williams [6]suggested that this long larval development period, swimming ability of puerulus, and the potential for mixing of the phyllosoma in eddies of the South-East Asian archipelago would result in low levels of population genetic structure for the species in the region. However, to date this hypothesis has not been tested.

The present study used molecular genetic techniques to elucidate the genetic population structure of *P. ornatus* within the South-East Asian archipelago. To explain the observed patterns of genetic structure, the potential dispersal pathway of *P. ornatus* was inferred based on a synthesis of data on regional oceanography and the lobster's known biology.

## Methods

### Tissue collections and DNA extraction

All work was done in compliance with the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes, and the Queensland Animal Care and Protection Act 2001 under Animal Ethics Permit no. A1746, as approved and administrated by James Cook University Animal Ethics Committee. Animals were collected from commercial aquaculture or fishery operations and no specific collection permits were required. Animals are not listed as endangered or threatened.

A total of 216 *Panulirus ornatus* individuals were sampled from two sites in Vietnam, three in Indonesia, and one in Australia (Fig 1). Specimens from Vietnamese populations were all pueruli, while those from Indonesia were juveniles at different age groups (17 samples at 150 g each collected in October 2009 and 15 samples at 20 g each collected in April 2010). Vietnamese lobster specimens came from the central coastal waters of the Da Nang (16 °N; 108 °E) and Binh Thuan (11 °N; 108 °E) provinces, while Indonesian samples were collected from North Sumatra (1°N; 97 °E), Lombok (9 °S; 116 °E) and West Timor (10 °S; 123 °E). Australian samples were collected from wild-caught Torres Strait juveniles (11 °S; 143 °E; 300 g each). All samples (pleopods from adults or abdominal muscle tissue from juvenile lobsters) were preserved immediately in a DMSO-salt preservative solution [21]. Genomic DNA (gDNA) from all lobster samples was extracted from 4 $mm^2$ pleopod clips or from the abdominal muscle tissue of juveniles using a modified CTAB protocol [22].

## Mitochondrial DNA (mtDNA) control region

Whole and partial genome sequences including mtDNA control regions of *Panulirus ornatus*, *P. gracilis*, *P. stimpsoni*, *P. japonicus*, and *P. inflatus* from the NCBI database were aligned using SEQUENCHER version 4.5 (GeneCode) and primers to amplify 809 base pairs of the mtDNA control region designed based on conserved sites using PRIMER3WEB version 3.0.0 (http://primer3.wi.mit.edu/). These primers were; PO_F2 5'—ATAAAGGTAATAGCAAGAA TC and PO_R1 5'—CAAACCTTTTGTCAGGCATC.

Extracted DNA from samples was diluted to 10–40 ng/μl for use in a polymerase chain reaction (PCR). The control region was amplified in 20 μl reaction volumes containing ~5 ng DNA, 1× TM buffer (Qiagen), 1.5 μM of $MgCl_2$, 0.2 μM of dNTPs, 0.1 μM of Tag Red (Qiagen) and 0.3 μM of forward and reverse primers. PCR was performed on a BioRadC1000 Thermal Cycler (cycling parameters: 3 min at 95°C, followed by 35 cycles of 95°C for 45 s, 50°C for 30 s, 72°C for 45 s, before a final extension step of 72°C for 5 min). PCR products were then run on a 1.5% agarose gel for quantity and quality verification, and subsequently cleaned-up to remove excess primers by precipitation with isopropanol [23]. A repeat region in the start of the reverse primed sequence resulted in deterioration of sequence. Consequently, only DNA sequence from the forward primer was used. To verify nucleotide base calls each sample was sequenced twice at the Australian Genome Research Facility (AGRF), Brisbane (Australia).

Sequence data were aligned using Geneious ver. 6.0.5 with default alignment parameters and were checked manually for misalignments. Poorly-aligned regions were removed using GBlocks with the default setting [24]. The nucleotide compositions and numbers of variable sites were assessed with MEGA6 [25]. Haplotype and nucleotide diversity for each location were estimated using DNAsp 5.1 [26], while neutrality tests (Tajima's *D* [27]) and partitioning of genetic structure $\Phi_{ST}$ (using genetic distance) as well as pairwise $\Phi_{ST}$ were calculated using ARLEQUIN 3.5 [28]. $\Phi_{ST}$ and pairwise $\Phi_{ST}$ comparisons between populations were estimated using the T92 model (Tamura 1992), with a gamma correction ($\alpha = 1.258$) as determined by Model Selection in MEGA6 [25]. For calculation of the statistical significance of $\Phi_{ST}$ values obtained, a significance test with 10,000 permutations was undertaken with ARLEQUIN 3.5 [28]. The median-joining network [29] for the haplotypes was constructed using Network v. 4.6.1.0 and Network Publisher v. 2.0.0.1 (http:\\www.fluxus-engineering.com) with default settings.

## Microsatellite markers

Ten highly polymorphic microsatellite markers [30] were used for population genetic investigations. DNA was diluted to 10–40 ng/μl for use as template in a polymerase chain reaction (PCR). Microsatellites were individually amplified in 10 μl reaction volumes containing ~20 ng DNA, 1× Type-it Multiplex PCR Master Mix (Qiagen), 0.04 μM of fluorescent labeled forward primer (TET, FAM or HEX), and 0.2 μM of reverse primer. PCR was performed on a BioRadC1000 Thermal Cycler (cycling parameters: 5 min at 95°C, followed by 28 cycles of 95°C for 30 s, 58°C for 90 s, 72°C for 30 s, before a final extension step of 60°C for 30 min). The PCR products then were checked for consistent amplification by visualization on a 1.5% agarose gel. After this step, PCR products were pooled according to size, fluorescent label, and product quantity and the pooled products were purified using Sephadex G-50 resin, before loading on a Megabace 1000 Capillary Sequencer for size separation of alleles (Amersham Biosciences). Alleles were scored on the basis of fragment size using Fragment Profiler 1.2 (Amersham Biosciences).

Summary statistics such as the number of alleles, as well as observed and expected heterozygosities, were calculated for microsatellites in GENALEX 6.1 [31], which was also used to test for deviations from Hardy-Weinberg Equilibrium (HWE). GENEPOP on the web (http://genepop.curtin.edu.au/) was used to test for linkage disequilibrium among microsatellite loci. Corrections for multiple comparisons (HWE and linkage disequilibrium) were adjusted using the False Discovery Rate (FDR) method [32]. Polymorphic Information Content (PIC) was also calculated for each locus with CERVUS 3.0 [33]. Null allele frequencies were analysed using FreeNA 3.0 [34] while the presence of null alleles and scoring errors were checked using MICROCHECKER 2.2.3 [35].

The level of genetic structure of *P. ornatus* based on microsatellite markers was analysed using an Analysis of Molecular Variance (AMOVA) with 10,000 permutations, as well as calculating pairwise $F_{ST}$ comparisons between populations, both of which were carried out with ARLEQUIN 3.5 [28]. Further to these analyses, the Bayesian clustering algorithm implemented in STRUCTURE ver. 2.3.4 [36] was used to determine spatial genetic discontinuities by inferring the highest probable number of genetic clusters present within the dataset with prior knowledge of the individual's origin. Individuals are placed in K predetermined sub-groups based on their likelihood of belonging to that sub-group calculated using allele frequencies of multiple loci. K was chosen in advance and ranged from one to 10 and the populations were assumed to be admixed (an individual could belong to any population) in origin. Burn-in and run length were set to 100 000 MCMC (Markov chain Monte Carlo) repetitions and each run was iterated 10 times. This approach implements a model-based clustering method for inferring population structure and assigning individuals to the most probable genetic sub-group or population. Structure Harvester (http://taylor0.biology.ucla.edu/structureHarvester/) was used to determine optimum number of clusters in this analysis. CLUMPP (http://www.stanford.edu/group/rosenberglab/clumpp.html) also was used to average across the replicate run and outputs were entered into DISTRUCT (http://www.stanford.edu/group/rosenberglab/distruct.html) to graph average q values.

The Indonesian samples were a mix of two different age groups (17 samples at 150 g collected in October, 2009 and 15 samples at 20 g collected in April, 2010). To test if there may have been temporally-induced genetic differences among these two collections we first undertook analyses treating each temporal sample as a separate collection. No evidence of genetic differentiation was evident among the temporally separated samples ($\Phi_{ST}$ = -0.0039; $F_{ST}$ = 0.0037; P >0.05) and accordingly we only report results from analyses for the Indonesian samples where we have treated them as a single population.

## Larval dispersal pathway map

Physical and biological data were integrated to develop a larval dispersal pathway map. A literature review was undertaken and expert opinion from relevant fisheries scientists in Australia, Vietnam and Indonesia was sought to identify data on spawning grounds and pueruli settling locations within the archipelago. One spawning ground is located in the southeast of the Gulf of Papua, Papua New Guinea (PNG), where Torres Strait lobsters spawn during the summer months from November to March [6, 19, 37, 38]. A second cluster of spawning grounds has been identified from the Philippines, where lobsters spawn from May to August [12, 39]. Other information included the observation that (a) 3 month old larvae appear in May-June at the southern tip of PNG [11, 37], and also on the eastern side of the Gulf of Papua also by May-June; (b) the central coast of Vietnam receives arrivals of pueruli in September-December in the North (15° N) and November to January in the South (12° N;[1, 7]); (c) another cohort of pueruli arrives to the Indian Ocean coast of northern Sumatra in November-December (Jones & Priyambodo, unpubl. data); and (d) Lombok receives two cohorts of *P. ornatus* pueruli, one cohort arriving in December-February and the second cohort arriving in August-November [1].

This biological data was then merged with oceanographic data to construct a map of the mean surface water circulation in the South-East Asian Archipelago, focusing on different months for different areas based on the known age of lobster larvae found during those months in those areas. We studied only the currents in the surface well-mixed layer, i.e. the layer above the thermocline, which in the tropics is typically about 100 m deep [40]. The *P. ornatus* larvae are found mainly within this layer [11] and it is only at the late-stage phyllosoma (i.e. older than 5 months) that the lobster can be found below the thermocline [41].The main data source of currents in the surface well-mixed layer was the ARGO program (http://www.aoml.noaa.gov/phod/argo/introduction_argo.php), but this had limited coverage for the South China, Philippines and Indonesian Seas. For those seas, the results of other field studies (listed in Table 1) were used, together with the results of the previous regional oceanographic models [13, 42–49], and for the South China Sea only (Daryabor, F.; unpubl. data). Streamlines were drawn representing the connectivity between sites where lobster data were available, using Microsoft Visio software v.2003.The length ($L$) between two sites was measured by Distance Calculator using Google Maps (http://www.mapdevelopers.com/distance_finder.php), not as a straight line, but as the length of the streamline of the flow field joining these two sites; and $u$ is the average speed of surface ocean current along that streamline during that period. Thus, the estimated time (t) for the larvae to reach different locations was calculated by Fischer [50],

$$\mathrm{t} = {}^{L}/_{u} \qquad (1)$$

# Results

## Genetic variation of the mtDNA control region

Nucleotide sequences of the control region were determined for 189 *P. ornatus* individuals (Genbank accession no. KJ956062-KJ956250). A small number of samples for which DNA was extracted failed initial quality control checks and were not successfully sequenced. From the 189 individuals sequenced successfully a total of 182 haplotypes were detected, with 601 sites without gaps and missing data and 231 were polymorphic (Table 2). Among 7 shared haplotypes, only one was shared among individuals at the same sampling site, six other haplotypes were represented at two sampling sites (S1 Table).

**Table 1. Field studies providing data of monthly-averaged currents in the surface-well mixed layer for the South-East Asian archipelago.**

| Author | Data source | Data Period |
|---|---|---|
| ARGO (2013) | Ocean drifters | 2000–2013 |
| Cravatte *et al*. [43] | ShipbornADCP | 1985–2007 |
| Condie [42] | NCEP-NCAR40-year Reanalysis dataset | 1982–1997 |
| Forbes and Church [44] | National Aeronautics and Space Administration (NASA) | 1978–1979 |
| Liang *et al*.[45] | ShipbornADCP | 1997–2001 |
| Manh and Yanagi [46] | | |
| Mayer *et al*. [47] | Data of the World Ocean Atlas | 1970–2006 |
| Metzger *et al*.[48] | Digital Bathymetric Data Base 2 (DBDB2) | 2004–2006 |
| Potemra and Qu [49] | National Oceanic and Atmospheric Administration (NOAA) | |
| Schiller *et al*.[13] | ARGO data | 1992–2006 |

ADCP = Acoustic Doppler Current meter.

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The *P*. *ornatus* mtDNA control region was found to exhibit an extremely high mutation rate, resulting in high haplotypic diversity whereby almost every lobster individual possessed a unique haplotype (Table 2). Haplotype diversities ranged from 0.997 to 1.000 within populations, while nucleotide diversities indicating the degree of polymorphism within a population/sample collection ranged from 0.020 (North Sumatra) to 0.034 (Lombok).

No significant population subdivision was detected among the populations sampled, with a non-significant fixation index evident ($\Phi_{ST}$ = -0.002; P = 0.648). All of the genetic variation measured with mtDNA occurred within populations, with no detectable among-population variance (Table 3). In addition, no evidence of individual population-level genetic structure was detected across the wide geographical range sampled from the Torres Strait of Australia to Vietnam and Indonesia, with negligible and non-significant pairwise $\Phi_{ST}$ values between populations being very low (from -0.042 to 0.010, P >0.05) (Table 4). Similar evidence for a lack of structuring was supported by the Tajima's *D* values, which were not significant at all localities (from -1.521 to -0.727, P >0.05) (Table 2). As further evidence for widespread gene flow and lack of genetic structure the haplotype network tree showed no clustering of haplotypes into geographical regions, or location based groups, with the majority of haplotypes being single or unique units (Fig 2). Therefore, mtDNA analyses based on the control region provided no evidence for genetic population structure in *P*. *ornatus* across the geographical range sampled.

**Table 2. Genetic indices for mtDNA control region characterized in *Panulirus ornatus* from six sample sites/collections.**

| Pop | *N* | *H* | *hd* | *Pi* | Tajima's *D (p-value)* |
|---|---|---|---|---|---|
| **Torres Strait** | 54 | 51 | 1.000 ± 0.004 | 0.028 ± 0.002 | -1,473 (0.088) |
| **West Timor** | 11 | 11 | 1.000 ± 0.039 | 0.029 ± 0.006 | -1.200 (0.136) |
| **Lombok** | 28 | 27 | 0.997 ± 0.010 | 0.034 ± 0.004 | -1.521 (0.088) |
| **North Sumatra** | 4 | 4 | 1.000 ± 0.177 | 0.020 ± 0.005 | -0.727 (0.279) |
| **Binh Thuan** | 51 | 51 | 1.000 ± 0.004 | 0.028 ± 0.003 | -1.859 (0.050) |
| **Da Nang** | 41 | 41 | 1.000 ± 0.005 | 0.026 ± 0.003 | -1.497 (0.088) |
| **Total/Mean** | 189 | 182 | 1.000 ± 0.001 | 0.028 ± 0.001 | -1.379 (0.089) |

*N*, sample size; *H*, number of haplotypes; *hd*, haplotype diversity; *Pi*, nucleotide diversity;

doi:10.1371/journal.pone.0124568.t002

**Table 3. Summary table of analysis of molecular variance (AMOVA) describing the partitioning of genetic variation for six *Panulirus ornatus* populations based on both mtDNA control region sequences and 10 microsatellite loci.**

| | Source of variation (%) | | | |
|---|---|---|---|---|
| | Among population | Within population | $\Phi_{ST}/F_{ST}$ | *p- value* |
| **mtDNA-control region** | -0.20 | 100.20 | -0.002 | 0.648 |
| **Microsatellites** | 0.26 | 99.74 | 0.003 | 0.195 |

doi:10.1371/journal.pone.0124568.t003

## Genetic variation of microsatellite markers

Ten polymorphic microsatellite markers were successfully amplified (Table 5) and PCR products of all 216 samples of *P. ornatus* were genotyped for subsequent population genetics analyses. A total of 143 alleles were observed, ranging from five (Orn_01) to 29 (Orn_11) alleles per locus. Significant departures from HWE were observed for two loci in the Lombok and Binh Thuan populations (Orn_01 in Lombok and Orn_17 in Binh Thuan) and the dataset was reanalyzed with and without these markers in these two populations to test if they were significantly influencing results obtained. No differences were found in genetic structure indices when these markers were included so the complete dataset of markers were analyzed and is presented here. No linkage disequilibrium was detected among the 10 loci genotyped. Null allele frequencies were above 10% at locus Orn_02 in Lombok (13%), at locus Orn_17 in West Timor (17%) and in Binh Thuan (15%) (S2 Table). Null allele frequencies also detected at loci Orn_16 (17%) and Orn_21 (11%) in North Sumatra, which could be the results of small samples size (4 samples). Dataset then were corrected and reanalysed. The results showed no difference in the AMOVA test and pairwise $F_{ST}$ estimates (S3 and S4 Table). The original dataset was therefore left unchanged.

As for the mtDNA control region, no significant population genetic structure was evident between the six sites when genotyped with the 10 microsatellite loci. $F_{ST}$ estimates of population structure were again negligible and non-significant (AMOVA, $F_{ST}$ = 0.003; P = 0.195) (Table 3). The microsatellite data indicated that less than 1% of genetic variation was present among populations. A similar lack of population genetic structure was evident in pairwise population comparisons across the Indo-West Pacific region ($F_{ST}$ ranged from -0.003 to 0.031, Table 4). The pairwise $F_{ST}$ comparison between North Sumatra and other sampling sites were the highest observed (from 0.017 to 0.034), but were all non-significant after FDR correction ($P > 0.05$). Due to the small sample size collected from North Sumatra the higher sample $F_{ST}$

**Table 4. Genetic differentiation between *Panulirus ornatus* from collection locations using pairwise $\Phi_{ST}$ for mtDNA-control region (upper value) and pairwise $F_{ST}$ for microsatellite loci (lower value).**

| | Australia | Indonesia | | | Vietnam | |
|---|---|---|---|---|---|---|
| **Localities** | **Torres Strait** | **West Timor** | **Lom-bok** | **North Sumatra** | **Binh Thuan** | **Da Nang** |
| Torres Strait | | 0.007 | 0.005 | -0.012 | 0.002 | 0.010 |
| West Timor | 0.006 | | -0.030 | -0.038 | -0.005 | -0.012 |
| Lombok | -0.003 | 0.008 | | -0.042 | -0.008 | -0.004 |
| North Sumatra | 0.029 | 0.030 | 0.034 | | -0.037 | -0.026 |
| Binh Thuan | 0.001 | 0.002 | 0.004 | 0.026 | | -0.006 |
| Da Nang | 0.000 | 0.009 | 0.001 | 0.017 | 0.002 | |

No significant value was found after correction using FDR.

doi:10.1371/journal.pone.0124568.t004

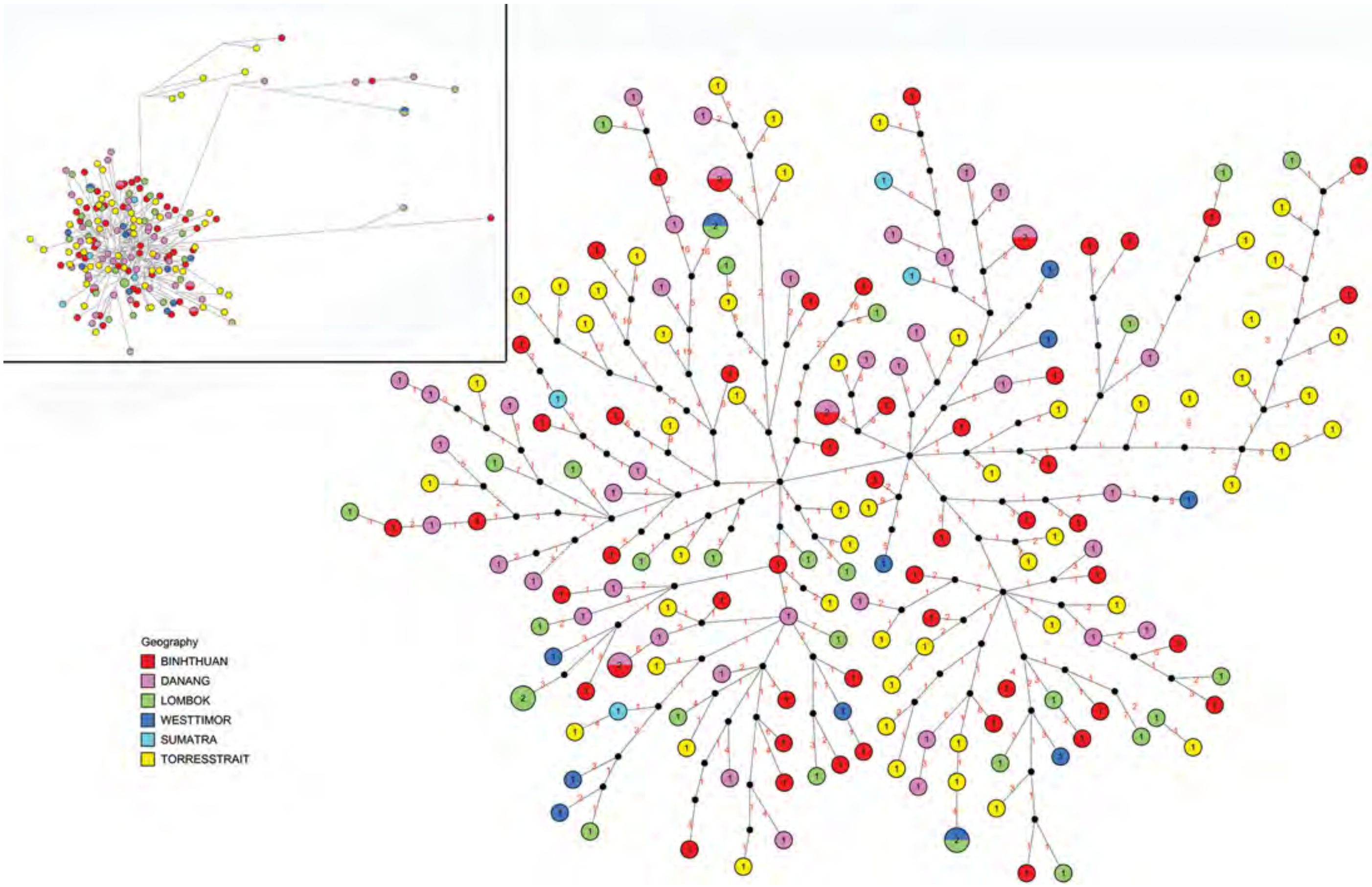


**Fig 2. Haplotype network of *Panulirus ornatus* control region sequences from six collection locations from the South-East Asian archipelago.** The larger tree on the right has been edited to show more detail, and the unedited tree is shown in the inset. Each circle represents a haplotype, whose diameter is proportional to the number of individuals with that haplotype. The black dots on the lines between haplotypes represent missing haplotypes. The numbers on the connecting lines are the number of mutations between haplotypes.

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values involving this population are likely a result of random sampling effects and small sample size.

Individual based Bayesian assignment tests supported the lack of population genetic structure indicated by non-significant and small pairwise $F_{ST}$ estimates. Although Structure Harvester suggests K = 2 from multiple simulations runs at values of K from 1 to 10, visual examination of individual bar plots for K = 2 indicates an inability of the STRUCTURE algorithm to reliably assign any of the individuals to a distinct cluster, with assignment probabilities for each of the two populations of ~50% for all individuals sampled in each of the 10 replicate runs (Fig 3). The inability to assign individuals using post-hoc plots if the true K < 2 has been discussed in Evanno *et al.* [51]. Therefore, Bayesian analysis using STRUCTURE, also suggests a lack of genetic structure, among the six populations examined, despite the widely spaced regional sampling employed here.

## Larval dispersal pathway map throughout the South-East Asian archipelago

The above genetic studies using both mtDNA control region and microsatellites reveal a single genetic population of *P. ornatus* within the South-East Asian archipelago, implying high

**Table 5. Genetic indices for 10 microsatellites characterized in *Panulirus ornatus* at six sample sites/collections.**

| | | Microsatellites | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Localities** | | **Orn 01** | **Orn 02** | **Orn 11** | **Orn 12** | **Orn 16** | **Orn 17** | **Orn 18** | **Orn 20** | **Orn 21** | **Orn 25** |
| **Torres Strait** | ***N*** | 72 | 72 | 71 | 71 | 71 | 70 | 72 | 69 | 71 | 70 |
| | $N_A$ | 8 | 4 | 20 | 23 | 9 | 10 | 9 | 10 | 7 | 9 |
| | $H_O$ | 0.72 | 0.54 | 0.85 | 0.94 | 0.79 | 0.5 | 0.74 | 0.42 | 0.79 | 0.71 |
| | $P_{HWE}$ | 0.98 | 0.93 | 0.98 | 0.76 | 0.98 | 0.98 | 0.98 | 0.98 | 0.92 | 0.98 |
| **West Timor** | ***N*** | 12 | 12 | 12 | 11 | 12 | 12 | 12 | 12 | 12 | 12 |
| | $N_A$ | 6 | 3 | 13 | 9 | 6 | 7 | 9 | 7 | 6 | 7 |
| | $H_O$ | 0.75 | 0.58 | 0.92 | 0.91 | 0.75 | 0.42 | 1 | 0.67 | 0.83 | 0.83 |
| | $P_{HWE}$ | 0.95 | 0.43 | 0.93 | 0.98 | 0.98 | 0.32 | 0.93 | 0.98 | 0.95 | 0.98 |
| **Lombok** | ***N*** | 32 | 32 | 32 | 32 | 32 | 31 | 32 | 30 | 32 | 32 |
| | $N_A$ | 10 | 3 | 20 | 19 | 8 | 7 | 10 | 7 | 8 | 7 |
| | $H_O$ | 0.69 | 0.41 | 0.88 | 1 | 0.84 | 0.45 | 0.69 | 0.3 | 0.72 | 0.63 |
| | $P_{HWE}$ | **0.00** | 0.32 | 0.11 | 0.98 | 0.56 | 0.95 | 0.98 | 0.98 | 0.98 | 0.93 |
| **North Sumatra** | ***N*** | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 3 | 3 | 3 |
| | $N_A$ | 3 | 3 | 5 | 4 | 5 | 2 | 5 | 1 | 3 | 3 |
| | $H_O$ | 0.33 | 0.67 | 1 | 1 | 0.5 | 0.67 | 1 | 0 | 0 | 1 |
| | $P_{HWE}$ | 0.93 | 0.95 | 0.95 | 0.98 | 0.75 | 0.93 | 0.98 | | 0.97 | 0.93 |
| **Binh Thuan** | ***N*** | 49 | 49 | 49 | 48 | 49 | 51 | 10 | 49 | 51 | 50 |
| | $N_A$ | 8 | 4 | 22 | 21 | 7 | 6 | 6 | 9 | 7 | 9 |
| | $H_O$ | 0.69 | 0.67 | 0.9 | 0.94 | 0.76 | 0.33 | 0.7 | 0.55 | 0.73 | 0.74 |
| | $P_{HWE}$ | 0.93 | 0.56 | 0.68 | 0.98 | 0.95 | **0.00** | 0.58 | 0.98 | 0.58 | 0.98 |
| **Da Nang** | ***N*** | 40 | 40 | 44 | 44 | 44 | 43 | 0 | 45 | 44 | 45 |
| | $N_A$ | 8 | 3 | 24 | 21 | 8 | 10 | 0 | 8 | 8 | 10 |
| | $H_O$ | 0.75 | 0.65 | 0.91 | 0.91 | 0.82 | 0.67 | 0 | 0.47 | 0.75 | 0.73 |
| | $P_{HWE}$ | 0.78 | 0.95 | 0.98 | 0.43 | 0.98 | 0.98 | | 0.98 | 0.95 | 0.98 |
| **Mean** | ***N*** | 34.67 | 34.67 | 35.17 | 34.83 | 35.33 | 35.00 | 21.50 | 34.67 | 35.50 | 35.33 |
| | $N_A$ | 7.3 | 3.5 | 17.2 | 16.0 | 7.3 | 6.8 | 6.3 | 7.0 | 6.33 | 7.3 |
| | $H_O$ | 0.70 | 0.60 | 0.91 | 0.89 | 0.74 | 0.49 | 0.69 | 0.39 | 0.69 | 0.77 |
| | ***PIC*** | 0.69 | 0.55 | 0.92 | 0.93 | 0.72 | 0.54 | 0.71 | 0.44 | 0.81 | 0.69 |
| **Total** | ***N*** | 208 | 208 | 211 | 209 | 212 | 210 | 129 | 208 | 213 | 212 |
| | $N_A$ | 11 | 5 | 29 | 26 | 11 | 16 | 11 | 14 | 8 | 12 |
| | ***Allele size range (bp)*** | 139–176 | 258–278 | 175–242 | 304–400 | 163–195 | 260–321 | 352–372 | 318–362 | 240–264 | 184–216 |

*N* sample size, $N_A$ number of alleles, $H_O$ observed heterozygosity, $P_{HWE}$ Hardy-Weinberg equilibrium significance value at $P<0.05$ after FDR correction, *ns* non-significant, *bold text* significant, *PIC* polymorphic information content.

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population connectivity of *P*. *ornatus* throughout this region. To explain how this connectivity may eventuate, the distribution of currents in the surface well-mixed layer in the South-East Asian archipelago is shown in Fig 4 for the larval transport periods listed in Table 6. From these data, the suggested connectivity network is shown in Fig 5 and further elaborated on in the discussion. Accordingly, the apparent lack of genetic structure in this tropical lobster species across South-East Asian archipelago is explained by current-mediated larval transport that connects lobsters among spawning populations. This connectivity requires at least three generations.

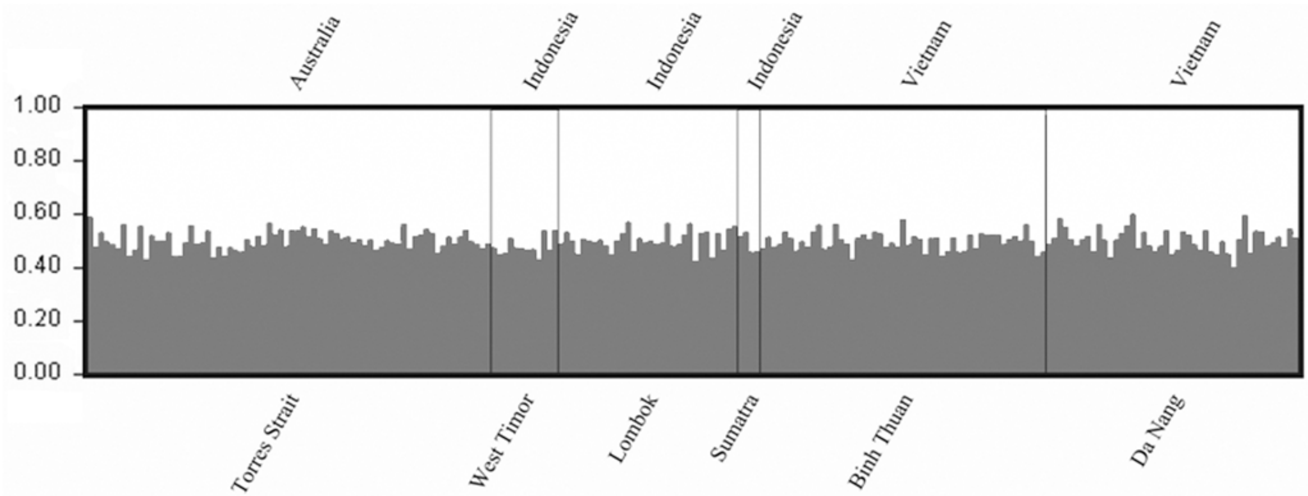


**Fig 3. Bayesian individual assignment analysis for K = 2 for *Panulirus ornatus* genotyped at ten microsatellites across six Indo-Pacific sampling sites.** Colours (grey or white) represent probability (y-axis) of individuals being assigned to each genetic cluster, whilst numbers (x-axis) represents population individuals sampled from 1 = Torres Strait, 2 = West Timor, 3 = Lombok, 4 = North Sumatra, 5 = Binh Thuan (Vietnam), 6 = Da Nang (Vietnam). Sampling locations were used as priors.

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# Discussion

## Genetic population structure

A combination of mitochondrial DNA control region and microsatellite DNA data suggest a single, genetically homogeneous stock of tropical ornate spiny lobster across a broad region of the South-East Asian archipelago. Genetic differences were not detected between samples of *P. ornatus* from Vietnam, Indonesia and Australia-PNG, supporting the hypothesis by Williams [6] of low genetic structuring of this species across the region due to its long oceanic larval development phase and wide larval transport capability. Neither population genetic ($F_{ST}$, $\Phi_{ST}$, Bayesian) or phylogeographic network analyses indicated any evidence for restrictions on gene flow across the region and integration of biological and oceanographic data show that genes can potentially circulate unimpeded throughout the entire region in only a few generations.

Similar occurrences of high population inter-connectivity have been observed in other *Panulirus* species and may be a consequence of the long larval dispersal and adult migration life-history within this genus of lobsters. For instance, genetic studies on Japanese spiny lobster, *P. japonicus*, failed to reveal any stock heterogeneity within the Japan Sea [52]. Low heterogeneity was also observed for *P. gilchristi* in South Africa [53] and *P. cygnus* in Western Australia [54]. However, the long pelagic larval duration of *Panulirus* lobsters does not always lead to low population divergence. In *P. argus*, for example, genetic differentiation is present between Bermuda and Florida populations within the Caribbean Sea, as well as those from Venezuela and Brazil [55]. Likewise, South African *P. delagoae* and *P. elephas* populations in the Atlantic Ocean and Mediterranean Sea exhibit shallow, but significant, levels of genetic structuring [56, 57]. Recently, high gene flow was found in *P. penicillatus* within localities in Western Pacific, but genetic structure was detected between Western and Eastern Pacific populations [58, 59]. In both study cases, the patterns of ocean currents were considered to be main factors contributing to larval dispersal and thus the population structure of spiny lobster species. Therefore, while life-history might play a part in determining genetic structure in this genus of lobsters, local oceanographic and other biogeographic factors largely drive the level of genetic structure that can be formed.

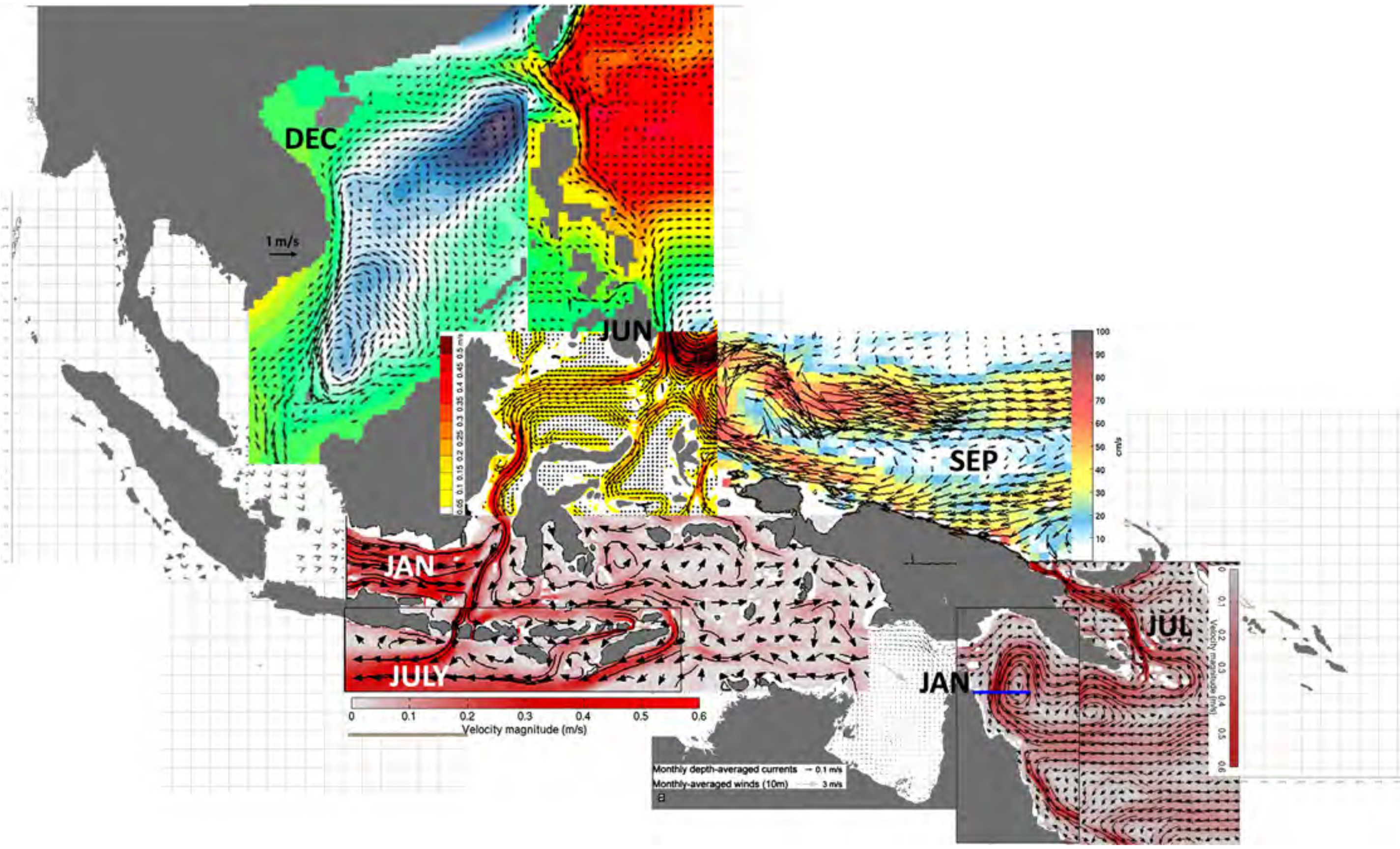


**Fig 4. Seasonal surface ocean currents in the surface well-mixed layer in the South-East Asian archipelago at the times when *Panulirus ornatus* larvae are travelling between the various sites shown in Fig 5, based on previous studies [13, 42, 45, 48, 49] and ARGOS data (http://www.aoml.noaa.gov/phod/graphics/dacdata/seasonal_wpac.gif).** To explain how this connectivity may eventuate, this figure shows the distribution of currents in the surface well-mixed layer in the South-East Asian archipelago during the periods of larval transport listed in Table 6.

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Regarding the mtDNA data presented in our study, previous papers have illustrated the point that inadequate sampling can lead to the wrong conclusions and for studies based on the mtDNA control region alone, in the situation where such high haplotypic diversity is evident within a species very large sample sizes can be required to detect common haplotypes and associate them with particular geographic areas [60, 61]. As a result, any conclusions made on levels of genetic structure based purely on the mtDNA control region data presented herein should be made with caution.

## Connectivity network and dispersal pathway

Our oceanographic informed dispersal modelling suggests the potential for complete connectivity of *P. ornatus* populations within the South-East Asian archipelago within three generations of breeding. Starting arbitrarily as the first generation from the spawning ground in the Gulf of Papua, with spawning known to occur from November to March (Fig 5), modelling suggests currents in this region would carry and split the resultant *P. ornatus* larva into two larval plumes; one plume is transported in a loop in the northwest Coral Sea to return to the Torres Strait, while the other plume exits the Coral Sea through the Vitiaz Strait to enter the Bismarck Sea where larvae are carried north-westward along the north-eastern coast of PNG from April to June. Timing is critical for the larvae of this second plume. If the larvae were to

**Table 6. Estimate time (*t*) for larvae/pueruli to reach different locations in the South-East Asian Archipelago, calculated from the length (*L*) between two sites, measured by Distance Calculator (http://www.mapdevelopers.com/distance_finder.php) and the average speed of current (*u*) in the surface well-mixed layer along that streamline during that period, inferred from modelling studies of different authors.**

| Route | Local Route | Author | Data time | Data depth (m) | *u* (cm/s) From | *u* (cm/s) To | *L* (km) | *t* (days) From | *t* (days) To | *t* (days) Average |
|---|---|---|---|---|---|---|---|---|---|---|
| PNG - | Gulf of Papua—Torres Strait | Schiller *et al*. [13] | Jan-Jul | < 250 | 10 | 15 | 1,361 | 105 | 157 | 105–157 |
| Australia - | Gulf of Papua—Bismack Sea | Schiller *et al*. [13] | Jan-Jul | < 250 | 15 | 30 | 1,381 | 53 | 107 | 49–107 |
| Philippines | | Cravatte*et al*. [43] | Jan-Jul | < 100 | 15 | 35 | 1,381 | 46 | 107 | |
| | Bismack Sea—Philippines/Banda Sea | ARGO (2013) | Jun-Sep | < 50 | 20 | 30 | 2,744 | 106 | 159 | 106–159 |
| | Luzon Strait—Central Vietnam | Manh and Yanagi [46] | Oct-Dec | ~ 0 | 15 | 20 | 1,416 | 82 | 109 | 76–109 |
| Philippines - | | Liang *et al*. [45] | Dec | < 50 | 15 | 20 | 1,416 | 82 | 109 | |
| Vietnam - | | Potemra and Qu [49] | Dec-Jan-Feb | < 100 | 15 | 25 | 1,416 | 66 | 109 | |
| Indonesia | Palawan—Central Vietnam | Liang *et al*. [45] | Dec | < 50 | 15 | 20 | 2,148 | 124 | 166 | 124–166 |
| | Central Vietnam—Java Sea | Liang *et al*. [45] | Dec | < 50 | 25 | 30 | 1,818 | 70 | 84 | 70–95 |
| | | Farshid (unpubl. data) | Dec-Jan-Feb | < 10 | 20 | 30 | 1,818 | 70 | 105 | |
| | Eastern Samar—Lombok | Liang *et al*. [45] | Jul | < 50 | 25 | 50 | 2,674 | 62 | 124 | 67–119 |
| | | Schiller *et al*. [13] | Jul | < 250 | 25 | 45 | 2,674 | 69 | 124 | |
| | | Potemra and Qu [49] | Mar-Apr-May | < 100 | 30 | 40 | 2,674 | 77 | 103 | |
| | | Metzger *et al*. [48] | Mean | < 120 | 25 | 50 | 2,674 | 62 | 124 | |
| Philippines - | North Lombok—South Lombok | Schiller *et al*. [13] | Jul | < 250 | 20 | 25 | 2,663 | 123 | 154 | 123–180 |
| Indonesia- | through Banda Sea | Mayer *et al*. [47] | Oct | < 700 | 15 | 25 | 2,663 | 123 | 205 | |
| Australia | South Lombok—North Sumatra | Schiller *et al*. [13] | Jul | < 250 | 15 | 20 | 2,114 | 122 | 163 | 122–163 |
| | | Potemra and Qu [49] | Jun-Nov | < 100m | 15 | 20 | 2,114 | 122 | 163 | |
| | Java Sea—Arafura Sea | Forbes and Church [44] | Jan | < 20 | 10 | 20 | 2,536 | 147 | 293 | 147–293 |
| | | Schiller *et al*. [13] | Jan | < 250 | 10 | 20 | 2,536 | 147 | 293 | |
| | | Condie [42] | Jan | < 18 | 10 | 20 | 2,536 | 147 | 293 | |

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arrive two months earlier along the north-eastern coast of PNG, they would be swept eastward into the Pacific Ocean by the Northern Equatorial Counter Current (NEC). Instead, larvae are carried through to the southern Philippines where they are dispersed widely by complex, swift currents through straits between islands from August to September (days 106 to 159 after spawning). This dispersal is facilitated by the directional swimming towards the shore of the pueruli during the last 25 days of development. After metamorphosis to the puerulus stage, lobsters settle to a benthic existence, where they progressively grow to maturity. It is unlikely they will move any great distance during this period, however, upon maturation adult lobsters may migrate up to a few hundred kilometres to the identified spawning grounds in the northern or western Philippines where they will spawn the second generation of larvae [4], [19, 61].

The second generation of larvae are produced from these adults on the east and west coasts of the Philippines from May to August. These larvae then potentially disperse in three plumes. The first plume is advected northward towards Taiwan (Fig 5). The second plume is transported into the South China Sea and reaches the central coast of Vietnam by September to December. This predicted timing of the arrival of pueruli in Vietnam given the time of spawning in the Philippines and ocean current models agrees well with field observations [1, 7]. Part of

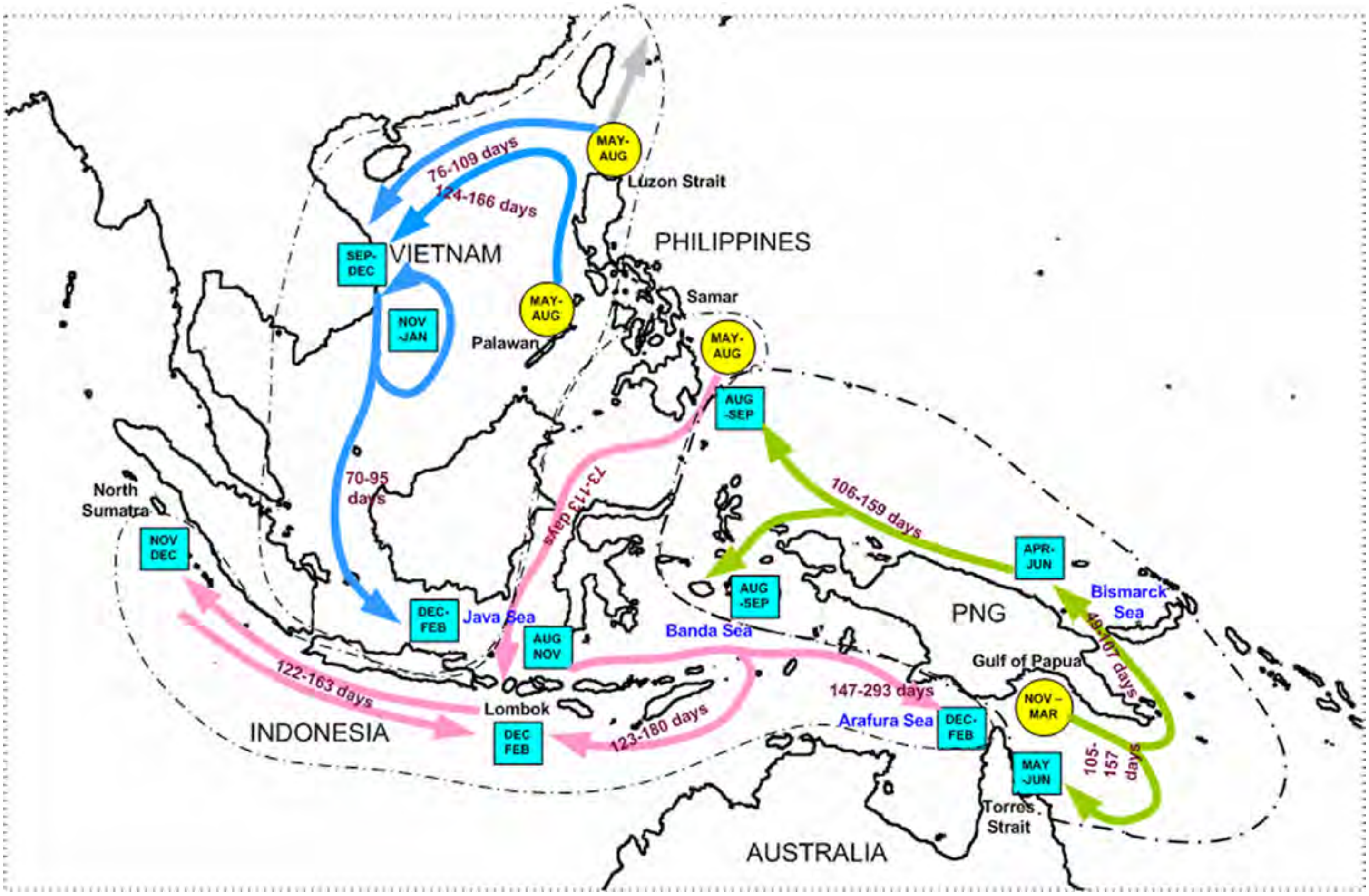


**Fig 5. Suggested larval dispersal pathways based on the surface water oceanography and the location of spawning grounds, dispersion patterns and connectivity for *Panulirus ornatus* larvae throughout the South-East Asian archipelago.** Round circles indicate spawning grounds where the larvae are released. Square boxes are estimated time that the larvae reach different locations as suggested by the oceanography and confirmed by field data; out of them only two points have no field data, namely arrival times of larvae from Lombok in Torres Strait and the time of transit of the larvae along the north coast of Papua New Guinea. The different colours represent the different putative larval dispersal pathways, in order to distinguish separate flows. Estimated time is presented in Table 6.

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this larval plume is further transported past Vietnam southward to Indonesia to reach Lombok 70–95 days later. The third larval plume originates from spawning grounds near Samar from May to August, from where newly-spawned *P. ornatus* larvae then would rapidly travel with the Mindanao Current southward to Lombok which they would reach in about 73–113 days. At that time the larvae are old enough to metamorphose into pueurli and settle and mature to become the third generation of adults. Spawning *P. ornatus* adults in Indonesia appear to produce two larval plumes. One plume originates in the south of Lombok and would travel with the Indonesian Throughflow to arrive in the Indian Ocean and ultimately to reach the Indian Ocean coast of northern Sumatra in November—December. These larvae are advected back towards Lombok during the northern winter monsoon (from November to February) before settling. The second larvae plume originates from the north of Lombok and is advected by currents to the Banda Sea and the northern Arafura Sea during the northern winter monsoon to reach Torres Strait waters by February. Evidence for these small juveniles (<40 mm carapace length) have been observed in Western Torres Strait [62]. We suggest that they will remain there until they mature as adults and can walk eastward across the Torres Strait to spawning grounds in the Gulf of Papua. The connectivity cycle is thus completed over three generations. Thus, based on the timing of the arrival of pueruli cohorts in Lombok and the time expected for dispersal of lobster larvae from Lombok to Torres Strait, we suggest that a third spawning ground exists in Indonesia, possibly around Lombok, but no field data are available. Likewise not all dispersal pathways are understood. Indeed some larvae originating from the Gulf of Papua may be transported southward towards the Java and Banda Seas, although there are no field data to confirm this suggestion.

In our study area the mean sea level was 100 m lower at the end of the last Ice Age about 20,000 years ago. At that time the Torres Strait was land and there was no connection between the Arafura Sea and the Coral Sea; in fact it is only about 8000 years ago that Torres Strait was flooded [63]. Thus the alternative explanation for our observations, namely that there was a formerly widespread population that subsequently became genetically differentiated, but with no apparent genetic signal yet due to incomplete sorting, appears unlikely.

### Implications for management

The existence of a single genetic population of *P. ornatus* characterised by drift connectivity [64] might have important implications for the sustainable management of this lobster in that the species within the region needs to be managed as one genetic stock. However, more work is required on the demographic connectivity of these populations so that the combined genetic and demographic connectivity datasets can inform management of this species as either one unit, or on the basis of individual spawning grounds [65].Consequently, a multi-governmental fishery policy should be developed by Australia, Papua New Guinea, the Philippines, Vietnam and Indonesia, to ensure sustainability. While the sinks of *P. ornatus* larvae are known, the knowledge of larval sources is still rudimentary, with to date only a few spawning sites confirmed. The present study suggests that an additional spawning ground may also be present in Indonesia, and its location needs to be identified and protected. More detailed studies on population connectivity are necessary to ensure the sustainability of lobsters in the South-East Asia archipelago. Genetic connectivity should be conserved as a priority.

## Conclusion

This study based on population genetic analyses at both mtDNA and nuclear DNA markers indicates high levels of connectivity among *P. ornatus* populations throughout the South-East Asian archipelago. The study is novel in terms of population dynamics because it suggests that this connectivity requires three generations for the cycle to complete and is reliant on timing of spawning events, time to settlement and prevailing ocean currents. These results have implications for fisheries management in the region, because there appears to be single stock of *P. ornatus*, which requires the engagement of governments and agencies to provide effective management policies for the benefit of all countries. A modelling study of larval transport processes over at least three generations is necessary to better locate the larval dispersal pathways and quantify the population dynamics including the relative influence of self-seeding versus broadcast connectivity between spawning populations.

## Supporting Information

**S1 Table. Spatial distribution of control region haplotypes among *Panulirus ornatus* from six localities in the South-East Asian archipelago.** http://dx.doi.org/10.5061/dryad.sp418/2. (DOCX)

**S2 Table. Null allele frequencies in the original dataset and after correction calculated by using FreeNA 3.0.** Values above 10% are in bold. http://dx.doi.org/10.5061/dryad.sp418/3.
(DOCX)

**S3 Table. Summary table of analysis of molecular variance (AMOVA) describing the partitioning of genetic variation for six *Panulirus ornatus* populations in the original dataset and after correction based on 10 microsatellite loci.** http://dx.doi.org/10.5061/dryad.sp418/4.
(DOCX)

**S4 Table. Genetic differentiation between *Panulirus ornatus* from collection locations using pairwise $F_{ST}$ for microsatellite loci in original dataset (lower value) and after correction (upper value).** No significant value was found after correction using FDR. http://dx.doi.org/10.5061/dryad.sp418/5.
(DOCX)

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## Author Contributions

Conceived and designed the experiments: HTD CSK EW DRJ. Performed the experiments: HTD. Analyzed the data: HTD. Contributed reagents/materials/analysis tools: CSK CMJ EW DRJ. Wrote the paper: HTD CSK EW CMJ DRJ.

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# Distribution and Abundance of Scyllarid and Palinurid Lobster Larvae in the Gulf of Carpentaria, Australia

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*Abstract*

Plankton samples from the Gulf of Carpentaria contained large numbers of the phyllosomata of *Scyllarus martensii* and an unknown scyllarid species (*Scyllarus* sp. A) and smaller numbers of the larvae of seven other scyllarid species (*Thenus orientalis* and six unidentified species of *Scyllarus*) and three palinurid species (*Panulirus homarus homarus*, *P. versicolor* and *P. ornatus*). The final phyllosoma stage of *Scyllarus* sp. A is described. The spatial and temporal variabilities of the more abundant scyllarid larvae are described and related to temperature, salinity and plankton biomass. Both *S. martensii* and *Scyllarus* sp. A were widespread in the deeper waters of the Gulf, living in a wide range of temperatures (21·7 to 30·3°C) and salinities (28·9 to 34·3). From the range of stages found on six cruises between April 1976 to March 1977, it appears that these two species reproduce throughout the year, although *S. martensii* had a broad peak period of reproduction from August to November 1976.

## Introduction

Few published accounts give quantitative information on the distribution and abundance of the larvae of the Palinuridae (rock or spiny lobsters) and Scyllaridae (slipper lobsters). Most of the literature is descriptive and deals mainly with the palinurid species of the well established lobster fisheries of temperate regions (e.g. Berry 1974; Lesser 1978; Booth 1979; Phillips 1981; Pringle 1986). Quantitative data on the distribution and abundance of lobster larvae in relation to temperature, salinity and other environmental factors are available for only two species: *Panulirus cygnus* George (Ritz 1972; Phillips *et al.* 1978, 1979; Rimmer and Phillips 1979) and *Scyllarus bicuspidatus* De Man (Phillips *et al.* 1981).

Although the zoogeographic distribution of the phyllosoma larvae of many tropical species of palinurids and scyllarids is known (e.g. Saisho 1966; Johnson 1971*a*, 1971*b*; Tampi 1973; Prasad *et al.* 1975; Tampi and George 1975), the ecology of these larvae in tropical waters has not been studied. The published literature is mainly descriptive. Preliminary surveys in the tropical East Pacific Ocean (Johnson 1971*a*) and in the South China Sea (Johnson 1971*b*) dealt briefly with larval distribution in relation to prevailing hydrographic conditions. Johnson (1971*b*) drew attention to the numerical predominance of scyllarid over palinurid larvae in shallow tropical seas of the Indo-West Pacific, such predominance also being apparent in data from the tropical western coast of Africa (Maigret 1978). Systematic ecological studies of single- or multi-species larval populations of tropical regions have not been undertaken. Consequently, there are no comparative data available on interrelationships of abiotic and biotic factors and the larval populations of tropical species.

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The Gulf of Carpentaria, northern Australia, supports a multi-species penaeid prawn (shrimp) fishery. Part of the incidental catch by prawn trawlers includes several species of the family Scyllaridae, particularly *Thenus orientalis* (Lund) (Barnett *et al.* 1984). However, the gulf has never been surveyed scientifically for adult lobsters. As part of studies of the larval ecology of penaeid stocks, a series of gulf-wide cruises was carried out from August 1975 to May 1977 (Rothlisberg and Jackson 1982). Although the sampling was designed to collect penaeid larvae, relatively large numbers of phyllosoma larvae were also taken. Samples obtained in six of these cruises in 1976 and 1977 were examined for phyllosomata, nistos and pueruli of the Scyllaridae and Palinuridae.

The gulf is a large (about $3 \cdot 7 \times 10^5$ km$^2$) shallow (<70 m) tropical embayment in northern Australia, lying between 11 and 17·5°S latitude and 136 and 142°E longitude (Fig. 1). Recent studies of the plankton biomass (Markina 1972; Motoda *et al.* 1978; Rothlisberg and Jackson 1982) and copepod communities (Othman *et al.* 1990) have shown

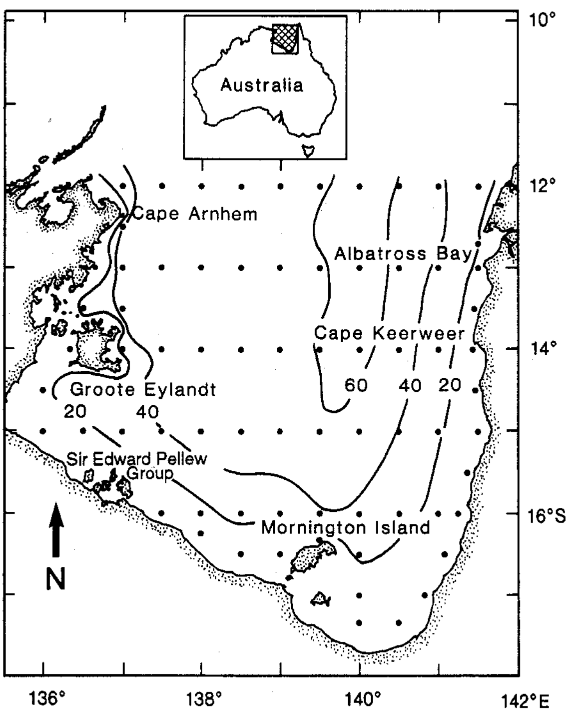


**Fig. 1.** Array of sampling stations in the Gulf of Carpentaria for cruises in 1976 and 1977. Depth contours in metres. Redrawn from Rothlisberg *et al.* (1987).

that the gulf has an abundant and diverse zooplankton community. The gulf's phytoplankton is dominated by diatoms and dinoflagellates (Hallegraeff and Jeffrey 1984). The distribution and abundance of penaeid prawn larvae (Rothlisberg *et al.* 1985, 1987) and the hydrographic milieu in which the early larvae were found (Rothlisberg and Jackson 1987; Rothlisberg *et al.* 1989) have been described. The hydrography of the gulf shows considerable geographic variation and seasonality in wind, tidal mixing, precipitation and evaporation (Forbes 1984). Most of these changes occur in the gulf, with limited exchange with the adjacent Coral and Arafura Seas.

In the present paper, the spatial and temporal variabilities of the more abundant scyllarid larvae are described and related to temperature, salinity and plankton biomass in order to provide ecological data on tropical scyllarid species.

## Materials and Methods

Plankton samples and hydrographic data were obtained from up to 70 stations (Fig. 1) on five of the six cruises carried out in the Gulf of Carpentaria between April 1976 and March 1977; the June–July 1976 cruise was restricted to 32 stations in the southern gulf (Rothlisberg and Jackson 1982). Plankton samples were obtained with paired nets with square $0 \cdot 5 \times 0 \cdot 5$-m mouth openings. Cylinder-cone nets—one with 142-$\mu$m mesh and the other with 500-$\mu$m mesh—were used simultaneously. Samples were taken at random times both day and night (see Rothlisberg and Jackson 1982). Stepped-oblique tows from surface to near-bottom with one or two intermediate steps were made at approximately 1 m $s^{-1}$ (2 knots). Water depth at stations varied from 7 to 65 m and, depending on depth and phytoplankton abundance, the towing time varied from 6 to 25 min, which filtered approximately 90 to 375 $m^3$ of water. After the nets were washed thoroughly by means of a salt-water hose, the plankton samples were recovered and fixed immediately with 4% buffered (sodium tetraborate) formaldehyde.

Each sample was initially split in half with a Folsom plankton sample-splitter. One half was dried for biomass analysis, as described by Rothlisberg and Jackson (1982), and the other half, or subsamples of this, was examined microscopically. Phyllosoma larvae were removed from the subsamples for identification of species and stages. The precision of the subsampling process was checked by sorting all of the subsamples of several 142-$\mu$m-net samples in which Stages I and II of *Scyllarus martensii* Pfeffer were present.

The staging criteria used for *Thenus orientalis* larvae corresponded to those of Barnett *et al.* (1984). The staging criteria for all species of *Scyllarus* were based on criteria used for *S. martensii* by Phillips and McWilliam (1986*a*). The criteria used to stage the larvae of all *Panulirus* species followed Johnson (1968).

Identification of a single late-stage larva of *Panulirus ornatus* (Fabricius) was based on Johnson's (1971*b*) description. The early larval stages (I–III) of *Panulirus homarus homarus* (Linnaeus) and *Panulirus versicolor* (Latreille) were identified from descriptions by Prasad and Tampi (1959), Johnson (1971*b*), Michel (1971) and Berry (1974). Where possible, material was compared with that held in the phyllosoma larvae reference collection established and maintained by one of the authors (B.F.P.) at the CSIRO Division of Fisheries, Marmion, Western Australia. Phyllosoma larvae from the present study have been added to the collection, and representative material will be lodged with the Western Australian Museum, Perth, Western Australia.

Larval abundance was standardized to number per 100 $m^2$ by using formula $d = ND/FV \times 100$, where $d$ is the number of larvae per 100 $m^2$, $N$ is the number of larvae sorted, $D$ is the sample depth (m) as recorded by a time–depth recorder, $F$ is the fraction of the original sample actually sorted, and $V$ is the volume of water filtered ($m^3$) as obtained from a calibrated flowmeter.

In this study, the catches of phyllosoma larvae from both nets were combined to provide a more representative collection of all stages of larval development. The relative efficiencies of the 142- and 500-$\mu$m-mesh nets in catching *S. martensii* and *Scyllarus* sp. A larvae were examined with a paired $t$-test. For each species, Stages I and VIII were analysed separately and the data for Stages II to VII were pooled. The data were transforemd to log $(x+1)$ for analysis, and a trimmed $t$-test was used to reduce the effect of outlying data points. The early larvae of *S. martensii* are slightly smaller than those of *Scyllarus* sp. A (Stage I, *S. martensii* $1 \cdot 00$–$1 \cdot 12$ mm and *Scyllarus* sp. A $1 \cdot 40$–$1 \cdot 50$ mm; Stage II, *S. martensii* $1 \cdot 13$–$2 \cdot 20$ mm and *Scyllarus* sp. A $1 \cdot 60$–$2 \cdot 40$ mm). Significantly more Stage I larvae of *S. martensii* were caught in the 142-$\mu$m net than in the 500-$\mu$m net ($t = 2 \cdot 86$, $P < 0 \cdot 01$, d.f. $= 246$). There was no significant difference in the pooled abundances of Stages II to VII. Significantly fewer Stage VIII larvae were caught in the 142-$\mu$m net ($t = 2 \cdot 54$, $P < 0 \cdot 05$, d.f. $= 246$). There were no significant differences between the catch rates of the two nets for any of the larval stages of *Scyllarus* sp. A.

Water samples were taken with reversing water bottles and their temperature measured *in situ* with reversing thermometers at the surface, at 10 m depth, and near the bottom. Salinity was measured in the laboratory with a temperature–salinity meter (Hamon 1956). The full suite of hydrographic sampling is described in Forbes (1984). Only temperature and salinity records from the near-bottom samples were used in the present study.

## Results

### *Species and Larval Stages*

The larvae of nine scyllarid and three palinurid lobster species were caught in the Gulf of Carpentaria (Table 1). The larvae of scyllarids were far more abundant than those of

**Table 1. Numbers of phyllosomata and nisto of Scyllaridae and Palinuridae sorted from Gulf of Carpentaria plankton**

| | Phyllosoma stage | | | | | | | | Nisto | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | | |
| Scyllaridae | | | | | | | | | | |
| *Scyllarus martensii* | 98 | 161 | 169 | 107 | 80 | 25 | 55 | 54 | 2 | 751 |
| *Scyllarus* sp. A | 30 | 82 | 173 | 89 | 81 | 26 | 18 | 11[A] | | 510 |
| *Scyllarus* sp. B | 3 | 10 | 5 | 1 | 2 | | | | | 21 |
| *Scyllarus* sp. C | 0 | 2 | 1 | 6 | 2 | 3 | 3[A] | | | 17 |
| *Scyllarus* sp. D | 0 | 1 | 1 | 0 | 1 | | | | | 3 |
| *Scyllarus* sp. E | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1[A] | | 1 |
| *Scyllarus* sp. F | 29 | 13 | 15 | 9 | 5 | 6 | 2[A] | | | 79 |
| *Scyllarus* sp. G | 4 | 21 | 9 | 7 | 6 | 2[A] | | | | 49 |
| *Thenus orientalis* | 5 | 9 | 2 | 0[A] | | | | | | 16 |
| Palinuridae | | | | | | | | | | |
| *Panulirus homarus homarus*[B] | 2 | 1 | 1 | | | | | | | 4 |
| *Panulirus ornatus*[B] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | | 1 |
| *Panulirus versicolor*[B] | 2 | 2 | 2 | | | | | | | 6 |

[A]Final phyllosoma stage in this species. [B]There are 11 phyllosoma stages in this species.

palinurids; larvae of *Scyllarus martensii* and *Scyllarus* sp. A were the most abundant. Complete larval series of four of the eight *Scyllarus* species were present (*S. martensii*, *Scyllarus* sp. A, *Scyllarus* sp. F and *Scyllarus* sp. G), and the series for *Scyllarus* sp. C was complete except for the first stage. All but the last stage of *T. orientalis* were caught. The early larval stages (usually Stage I) of all species except *Scyllarus* sp. F were under-represented. All of the above species are obviously capable of completing their larval phase within the gulf. However, the only postlarvae caught were nisto stages of *S. martensii*, although adults of this species have not been recorded from the gulf.

The larvae of the three species of palinurid lobsters were very rare and most were in the earliest stages; no phyllosomata beyond Stage VIII were collected. Ten of the 11 palinurid larvae were collected along the two northernmost transects; the eleventh was a late-stage *P. ornatus* larva at the most north-easterly sampling station (Fig. 1). No adults of *Panulirus* species have been recorded from the gulf.

### *Larval Description*

#### *Scyllarus sp. A, Stage VIII—final (gilled) stage*

Eleven specimens of the final (gilled) stage of this species were caught; their range in total length was from 19·5 to 23·0 mm. The morphometrics of the specimen illustrated (Fig. 2) are: total length 19·5 mm; cephalic shield length 12·0 mm; cephalic shield width 12·2 mm; thorax width 7·6 mm; pairs of exopodal setae on pereiopods: P1 = 24, P2 = 23, P3 = 22, P4 = 20.

The cephalic shield is subcircular, slightly wider than long, with a moderately truncated posterior margin. The eyestalk is longer than the antennule, which has three faint peduncular segments. The antenna has three segments; its inner ramus has a serrated inner distal margin and is almost twice as long as the outer process. There is a small rudimentary exopod on the second maxilliped and a minute bud on the third maxilliped. Fine ventrally directed coxal spines are present on the first to fourth pereiopods. There is also a relatively small spine on the third maxilliped and fifth pereiopod. The fifth pereiopod has five segments, with a lateral spine at the distal end of the second segment; the distal segment extends beyond the posterior margin of the telson. The first four pereiopods have curved subexopodal spines. The abdomen is broadly confluent with the thorax and has long, slender, biramous pleopod

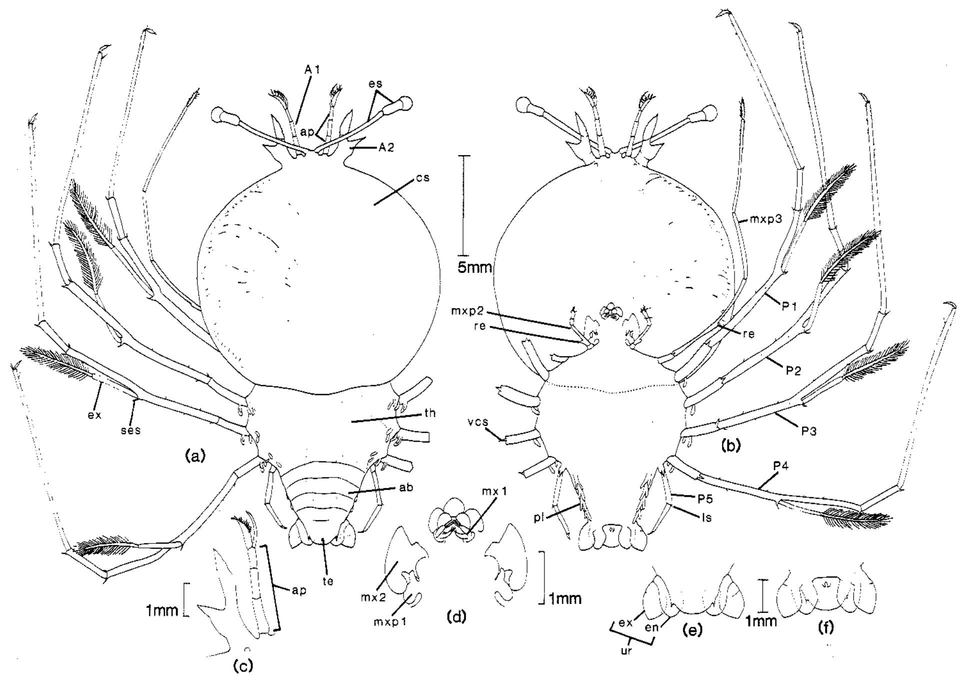


**Fig. 2.** Final (gilled) stage of *Scyllarus* sp. A: (*a*) dorsal view; (*b*) ventral view; (*c*) antennule and antenna; (*d*) mouthparts and first maxilliped; (*e*) uropods and telson (dorsal); (*f*) uropods and telson (ventral). A1, antennule; A2, antenna; ab, abdomen; ap, antennular peduncle; cs, cephalic shield; en, endopod; es, eyestalk; ex, exopod; ls, lateral spine; mx1 and mx2, first and second maxilla; mxp1 to mxp3, first to third maxilliped; P1 to P5, first to fifth pereiopod; pl, pleopod; re, rudimentary exopod; ses, subexopodal spine; te, telson; th, thorax; ur, uropod; vcs, ventral coxal spine.

buds; no appendices internae buds are present. The telson has a pair of strong lateral spines and a moderately convex distal margin. The uropods have spatulate rami, and the exopods are slightly angular distally.

### *Distribution and Abundance*

#### *Scyllarus martensii*

Stage I larvae were widespread from north-west of Mornington Island up through the deeper parts of the central gulf (Fig. 3*a*). Stages II through VII were even more widespread

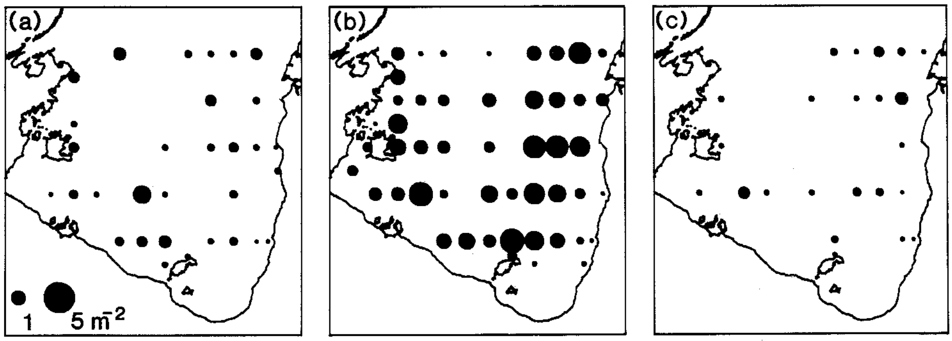


**Fig. 3.** Distribution and abundance of phyllosomata of *Scyllarus martensii* in the Gulf of Carpentaria: (*a*) Stage I; (*b*) Stages II–VII; (*c*) Stage VIII. The number of phyllosomata per square metre is directly proportional to the area of each solid circle (see key).

in the gulf, with the largest abundances in the eastern half (Fig. 3*b*). Stage VIII (the final, gilled, larval stage) was found predominantly in the eastern gulf, with the highest abundances in the north-eastern sector (Fig. 3*c*). The two nistos were collected in a single sample in the central-eastern gulf in 53 m of water (15°1·5′S,140°9·0′E).

Hatching of *S. martensii*, as indicated by the presence of Stage I larvae, apparently takes place throughout the year, with a protracted peak from June to November (Table 2). The mean densities, over all larval stages, also peak between August and November, prior to the summer wet season. The relationship between mean density and stage clearly shows a low abundance of Stage I larvae and a linear reduction in density from Stages II to VIII (Fig. 4*a*). A two-way analysis of variance of the time (cruise) and stage data confirmed that the differences in the density of the stages were statistically significant ($P<0\cdot001$).

**Table 2. *Scyllarus martensii* larval abundance (mean density, number per 100 m$^2$, over all stations occupied per cruise) in the Gulf of Carpentaria**

| Cruise date | Phyllosoma stage I | II | III | IV | V | VI | VII | VIII | Total |
|---|---|---|---|---|---|---|---|---|---|
| April–May 1976 | 7·78 | 17·23 | 15·73 | 9·66 | 10·99 | 1·95 | 7·82 | 7·26 | 78·42 |
| June–July | 10·98 | 3·95 | 5·31 | 2·50 | 2·72 | 0·45 | 1·59 | 0·95 | 28·45 |
| August–September | 13·26 | 18·45 | 24·09 | 20·06 | 4·88 | 4·38 | 2·11 | 1·20 | 88·43 |
| October–November | 18·79 | 29·95 | 29·48 | 21·77 | 11·28 | 3·96 | 11·37 | 16·24 | 142·85 |
| January 1977 | 4·83 | 12·05 | 16·54 | 8·49 | 10·03 | 1·89 | 6·52 | 1·78 | 62·14 |
| March | 5·64 | 18·57 | 5·77 | 6·38 | 5·98 | 1·29 | 2·78 | 0·93 | 47·35 |

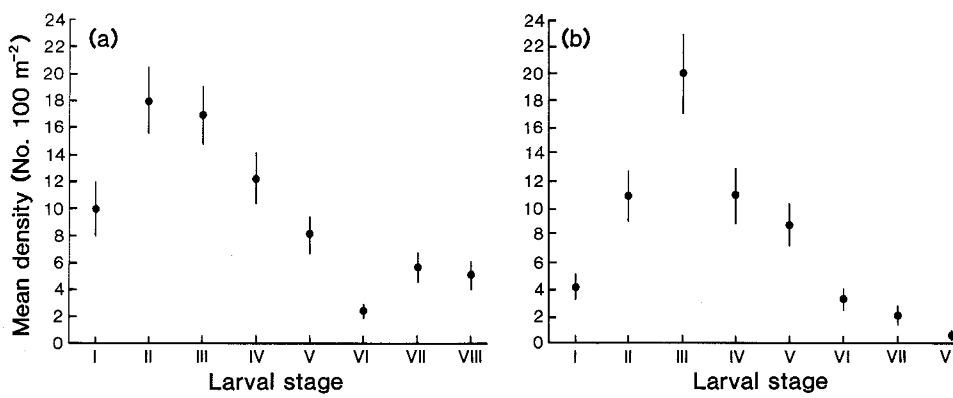


**Fig. 4.** Mean densities (±1 s.e.) of each larval stage over the six cruises in the Gulf of Carpentaria: (*a*) *Scyllarus martensii*; (*b*) *Scyllarus* sp. A.

*Scyllarus sp. A*

The distribution of *Scyllarus* sp. A larvae in the gulf differed from that of *S. martensii* (Fig. 5). Stage I larvae were found almost exclusively in the central and western gulf (Fig. 5*a*). Stages II through VII were widespread but were most abundant in the western gulf and very rare in the southern gulf (Fig. 5*b*). Very few Stage VIII larvae were found, but most were in the northern and north-western gulf (Fig. 5*c*).

Hatching takes place throughout the year, with a peak in Stage I larvae in October–November (Table 3). There is some evidence of bimodal peaks in November and March in the later larval stages and in overall abundance. Both Stages I and II had low densities. After peaking at Stage III, density declined steadily (Fig. 4*b*). A two-way analysis of

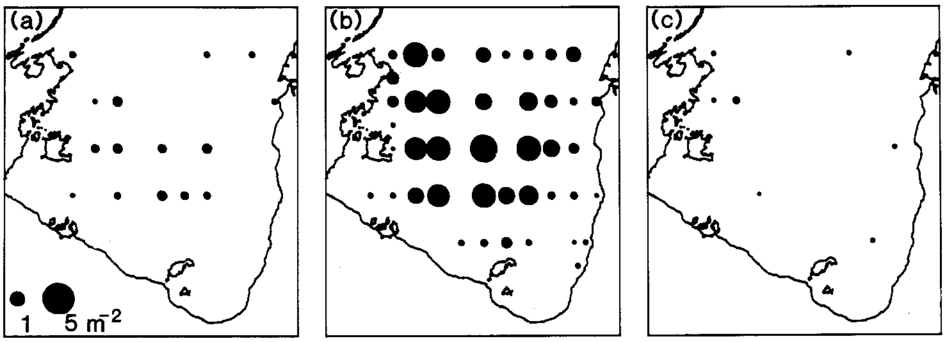


**Fig. 5.** Distribution and abundance of phyllosomata of *Scyllarus* sp. A in the Gulf of Carpentaria: (*a*) Stage I; (*b*) Stages II–VII; (*c*) Stage VIII. The number of phyllosomata per square metre is directly proportional to the area of each solid circle (see key).

**Table 3. *Scyllarus* sp. A larval abundance (mean density, number per 100 m$^2$, over all stations occupied per cruise) in the Gulf of Carpentaria**

| Cruise date | Phyllosoma stage | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | |
| April–May 1976 | 3·96 | 9·08 | 15·24 | 8·45 | 10·64 | 3·74 | 2·73 | 2·05 | 55·89 |
| June–July | 0·00 | 1·16 | 0·54 | 5·42 | 3·59 | 1·81 | 0·00 | 0·00 | 12·53 |
| August–September | 2·33 | 20·32 | 17·52 | 8·16 | 7·76 | 6·03 | 3·15 | 0·00 | 65·26 |
| October–November | 8·41 | 13·26 | 31·27 | 17·68 | 15·59 | 4·01 | 3·72 | 1·03 | 94·97 |
| January 1977 | 4·14 | 5·76 | 16·52 | 4·76 | 3·73 | 1·99 | 1·99 | 0·50 | 39·39 |
| March | 3·85 | 17·72 | 28·57 | 17·80 | 8·77 | 2·83 | 0·00 | 0·00 | 79·55 |

variance of the time (cruise) and stage data confirmed that the differences in the density of the stages were statistically significant ($P<0\cdot05$).

*Relationship of Larvae to the Environment*

The relationship between the occurrence of all larval stages of the two most abundant species (*S. martensii* and *Scyllarus* sp. A) and the temperature and salinity of the waters in which they were found was investigated. Even with these two species, the high proportion of zero abundances caused some difficulties in analysis, and it was judged most appropriate to analyse the data simply with respect to presence or absence. Over all stations sampled, temperatures ranged from 19·8 to 31·2°C, with a mean of 27·4°C, and salinities ranged from 26·2 to 34·4, with a mean of 32·9 (Fig. 6*a*). Stations where *S. martensii* occurred had a mean temperature of 27·3°C, ranging from 21·7 to 30·3°C, and a mean of salinity of 33·3, ranging from 28·9 to 34·3 (Fig. 6*b*). Stations where *Scyllarus* sp. A occurred had a mean temperature of 27·8°C, ranging from 23·3 to 30·2°C; the mean salinity at these stations was 33·5, ranging from 29·6 to 34·2 (Fig. 6*c*).

To assess the potential importance of environmental factors to reproductive activity, the presence of Stage I larvae (i.e. hatching) was analysed, using a multiple regression with respect to cruise, depth of station, time of day, temperature, salinity and plankton biomass. Time of day was modelled by a two-parameter sine curve, and depth, temperature, salinity and biomass were modelled by linear coefficients. Since any clustering of the small number of occurrences might lead to apparently significant interactions, no interaction effects were included in the analysis.

Temperature, salinity and biomass did not have a significant relationship with Stage I larval occurrence for either species (Table 4). For *S. martensii*, cruise accounted for 2·69%

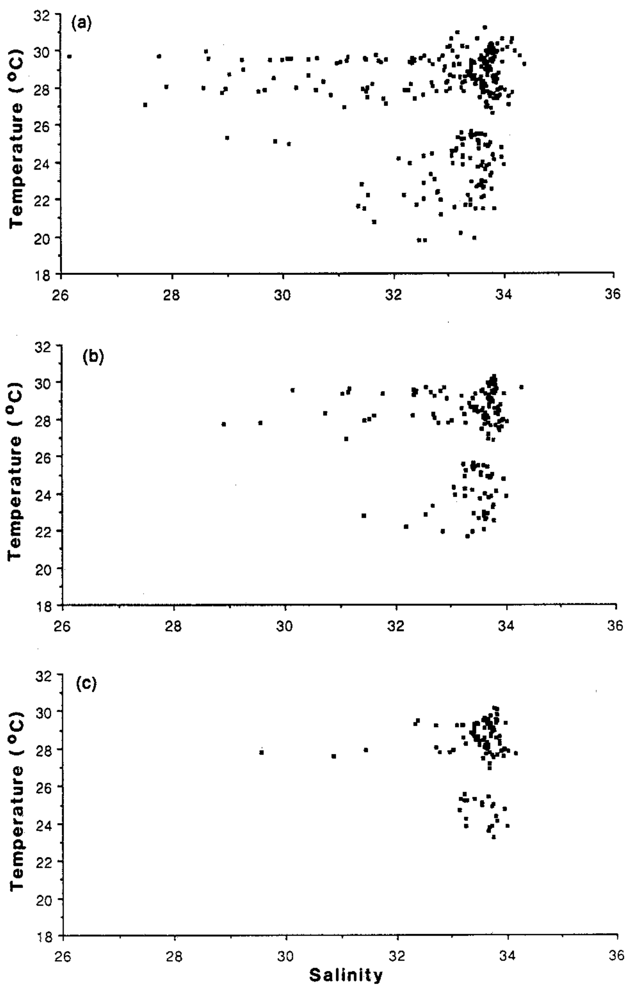


**Fig. 6.** Temperatures and salinities in the Gulf of Carpentaria: (*a*) all stations sampled; (*b*) stations where *Scyllarus martensii* occurred; (*c*) stations where *Scyllarus* sp. A occurred.

**Table 4. Analysis of variance: regression of Stage I larval occurrence against cruise, depth, time of day, temperature, salinity and plankton biomass**

The factors were fitted in the order shown in the table, and the $F$-tests have been adjusted for factors previously entered into the model. $^{+}0\cdot10>P>0\cdot05$, $^{*}P<0\cdot05$, $^{***}P<0\cdot001$

| Source | d.f. | *Scyllarus martensii* Percentage of variance | *Scyllarus martensii* $F$-ratio | *Scyllarus* sp. A Percentage of variance | *Scyllarus* sp. A $F$-ratio |
|---|---|---|---|---|---|
| Cruise | 5 | 3·41 | 2·69* | 1·69 | 1·41 |
| Depth | 1 | 0·93 | 3·67+ | 6·63 | 27·66*** |
| Time of day | 2 | 0·24 | 0·47 | 0·40 | 0·83 |
| Temperature | 1 | 0·08 | 0·34 | 0·36 | 1·50 |
| Salinity | 1 | 0·20 | 0·79 | 0·16 | 0·69 |
| Plankton biomass | | | | | |
| 142-$\mu$m mesh | 1 | 0·01 | 0·05 | 0·35 | 1·45 |
| 500-$\mu$m mesh | 1 | 0·05 | 0·20 | 0·37 | 1·54 |
| Error | 376 | 95·08 | 0·1102 | 90·05 | 0·0497 |

of the variation ($P<0 \cdot 05$), indicating significant differences in reproduction between months. Depth was almost a significant factor ($0 \cdot 10>P>0 \cdot 05$), the positive relationship indicating a higher occurrence of hatching in deeper water. For *Scyllarus* sp. A, depth was the only significant factor ($P<0 \cdot 001$), coinciding with the even more restricted distribution of Stage I larvae in the deeper central gulf (Fig. 5*a*).

## Discussion

### *Species and Larval Stages*

This study has supplied preliminary quantitative data on the larval ecology of lobster populations in a large, shallow, tropical embayment. These data indicate that the Gulf of Carpentaria supports the larval development of a fairly diverse lobster community, dominated by scyllarid species. The preponderance of scyllarid over palinurid larvae caught in the gulf is similar to findings for phyllosomata collected in the South China Sea (Johnson 1971*b*) and off the north-western coast of Africa (Maigret 1978). Johnson (1971*b*) also found that larvae of two scyllarid species (*S. martensii* and his *Scyllarus* sp. D) predominated in the South China Sea.

The large number of *S. martensii* caught in this study (751) is surprising; all stages of development were represented, which clearly indicates the likely presence of considerable numbers of adults. However, no adults have been reported from the gulf (B. Long, I. Poiner and T. Wassenberg, personal communication), although they have been recorded from the eastern coast of northern Queensland (P. Davie, Queensland Museum, personal communication). Because *S. martensii* is an extremely small species (up to 36 mm long, including antennae; Holthuis 1947), it is not likely to be kept by commercial fishermen, the principal source of taxonomic material from this region.

The second most abundant phyllosomata were *Scyllarus* sp. A of unknown identity. The complete larval series of this species, and of the latest stages found of the unidentified *Scyllarus* spp. B–F, will be described in a separate paper.

Although *Thenus orientalis* is the most common scyllarid in commercial prawn trawl catches in the gulf, the present sampling programme caught only 16 larvae, none of which was at the final stage (IV). Johnson (1971*b*) also noted a paucity of *T. orientalis* larvae in his South China Sea catches: 20 (Stages I–III only) in a total collection of 2118 scyllarid larvae. Barnett *et al.* (1984) caught 815 specimens of *T. orientalis* of all stages, including Stage IV, in a daytime sampling programme off Townsville, eastern Australia. The larvae of *T. orientalis* are relatively large (Stage I mean total length 3·6 mm, $n=371$; Barnett *et al.* 1984), compared with those of *S. martensii* (Stage I range 1·0–1·1 mm) and *Scyllarus* sp. A (Stage I range 1·4–1·5 mm), and they have an enhanced swimming—and probably net-avoiding—ability because their pereiopodal exopods with natatory setae are at a more advanced stage of development at hatching. Barnett *et al.* (1984) used a net with a mouth opening of 3·37 $m^3$ and sampled only in relatively shallow (4–40 m) coastal water inside the Great Barrier Reef. Because Barnett *et al.* (1984) did not report tow duration, volumes of water filtered, or larval densities, abundances between the two studies cannot be directly compared. It is likely that the relatively high numbers of larvae than those authors caught reflect the larger mouth opening of the net, the larger volumes of water filtered, and an emphasis on collecting in the inshore (within 10 n miles) zone. This compares with our sampling across the entire gulf in depths from 7 to 65 m, using a net with a mouth opening of 0·25 $m^2$.

Although *Panulirus* adults have not been recorded from the gulf, the occurrence of *P. homarus homarus*, *P. ornatus* and *P. versicolor* larvae is not surprising because these species are widespread in the Indo-West Pacific (George and Holthuis 1965). The presence of early larvae of *P. homarus homarus* and *P. versicolor* suggests that they were hatched from adults in or near the gulf. The absence of mid- and late-stage larvae of these species in our samples is not unexpected because they have usually been found in oceanic conditions

(Phillips and McWilliam 1986*b*) and the shallow Gulf of Carpentaria may be unsuitable for their development. Therefore, without late larval stages and probably suitable nursery habitats, population maintenance in the gulf could require migrations of adults, as has been demonstrated for *P. ornatus* in the Gulf of Papua (Bell *et al.* 1987).

*Distribution and Abundance*

The phyllosoma larvae of *S. martensii* and *Scyllarus* sp. A are widely distributed in the gulf. This may be a consequence of the ovigerous females being widely distributed or of larvae hatching in deeper water and dispersing widely. Penaeid prawn larvae in this region can disperse as far as 165 km during their short (two to three weeks) planktonic life (Rothlisberg 1982; Rothlisberg *et al.* 1983). As the larvae of scyllarid species live in the plankton for one to four months (for review, see Phillips and Sastry 1980), they can presumably also disperse over greater distances.

The densities of *S. martensii* Stage I larvae and *Scyllarus* sp. A Stages I and II were surprisingly low in the samples. Because we combined the samples from the 142- and 500-$\mu$m nets, net selectivity (i.e. mesh escapement) does not explain the low numbers. The stepped-oblique sampling technique used in this study is adequate for sampling the larvae of the penaeids in the gulf. These larvae, which migrate vertically through the full water column, are equally abundant during the day and at night (Rothlisberg *et al.* 1987). However, if any phyllosoma stages are concentrated near the surface (as observed by Phillips 1981) or bottom (as suggested by Johnson 1971*a*), oblique sampling would underestimate them. Another possibility is that the duration of earlier stages (I–II) is very much shorter than that of later stages (Robertson 1968), so the early-stage larvae would be relatively less abundant.

There was some evidence of seasonality of reproduction and larval abundance of *S. martensii*. The peak of abundance for all larval stages occurred between late August and mid November, indicating one hatching per year and a larval life span of two to three months. There is a slight increase on the estimates of one to two months for other tropical scyllarids (Robertson 1968, 1971). No clear temporal pattern in the larval abundance of *Scyllarus* sp. A was seen. Perhaps the reproductive season is more protracted and/or the larval development period is longer than that for *S. martensii*. The reduction in mean abundance of Stages II to VIII of *S. martensii* (Fig. 4*a*) and III to VIII of *Scyllarus* sp. A (Fig. 4*b*) suggests that mortality is high. However, since the duration of the larval stages is unknown, absolute mortality rates cannot be estimated.

*Relationship of Larvae to the Physical Environment*

The present study appears to be the first attempt to relate larval distribution of tropical scyllarid species to environmental factors. In this study, both *S. martensii* and *Scyllarus* sp. A occurred over a wide range of temperatures and salinities, although they were found most frequently in waters with both high temperatures (27 to 33°C) and high salinities ($\geqslant 33 \cdot 0$). Phyllosomata were seldom found in the shallow waters of the southern and western gulf, possibly because salinity is seasonally lowered in these areas by runnoff from several rivers (Forbes 1984). Rothlisberg and Jackson (1987) reported that the larvae of four species of penaeids in the gulf were found in different hydrographic conditions. They suggest that this reflects species-specific differences in larval tolerance and/or spawning conditions. However, the present study found no relationship between hatching (i.e. Stage I occurrence) and these hydrographic conditions for these two species of *Scyllarus*. Further investigations might elucidate such relationships, especially if early larval abundance has been underestimated in the present study.

Additional studies, with sampling strategies optimized for phyllosomata, are necessary to fully understand the full suite of species present and the factors affecting their recruitment. Of equal importance is a complete benthic faunal survey to quantify the distribution, abundance and reproductive dynamics of adult lobsters.

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# Estimation of the abundance of the tropical lobster *Panulirus ornatus* in Torres Strait, using visual transect-survey methods

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**Abstract.** The *Panulirus ornatus* stock in a 25000 km$^2$ area of Torres Strait was estimated by making visual counts of the number of lobsters in strip transects. Pilot studies in 1988 to assess the feasibility of a full-scale survey and optimize the sampling design showed that: 4 × 500 m transects were the most cost-effective of the different sizes trialled; two transects per location comprised the most optimal allocation of replication; and ~300 locations were necessary to achieve a 95% confidence interval of ±10% of the mean density found in the pilot study. Satellite imagery was used to map habitats in Torres Strait, and areas likely to be inhabited by lobsters were classified broadly into three strata: windward reef slope, submerged reef, and deep areas. The 300 locations were allocated to each stratum in proportion to its area and the estimated variance of lobster abundance within it; once allocated, the locations were positioned at random within each stratum. The main survey was undertaken over a period of 7 wk in May–June 1989, and the resulting estimate of lobster abundance was ~14 million with a 95% confidence interval of ±21%. The surveyed population was sampled concurrently to determine its size structure: the pre-fishery year-class comprised 43% of the population; lobsters greater than legal-size comprised 57% and their average tail weight was 346 g. Thus, the estimate of stock size for the study area was 2200 to 3350 t tail weight, which is roughly ten-fold greater than the annual catch of about 250 t. The current catch is approaching the lower estimates of potential yield, calculated using simple maximal sustainable yield estimators, which suggests that the fishery is unlikely to be under threat at present and may support greater effort.

## Introduction

The fishery for the ornate tropical rock lobster, *Panulirus ornatus*, is the major industry for Australia's Torres Strait Islanders and further expansion of the fishery is reserved for Islanders (Channells 1986). The same stock supports Papua New Guinea's second largest domestic fishery. As with any other fishery, orderly managed expansion would be facilitated by knowledge of the potential yield. The usual method of estimating potential yield, by analysis of catch and effort data, is not suitable for the Torres Strait dive fishery because only part of the effort is monitored and these records began only recently. Consequently, an alternative approach to estimating potential yield from information on absolute stock size was considered. This approach would also provide valuable input for the development of fishery dynamics models.

Of the few attempts to estimate the absolute abundance of spiny lobsters, most have used tagging methods (Morgan 1980), which are often subject to serious error problems and biases (Morgan 1974, Gulland 1983). Obviously it was desirable to avoid these problems. As these lobsters are fished by divers, and the depth of Torres Strait in the vicinity of the fishery is rarely greater than 25 m, it was logical for research divers to attempt a direct visual census of the lobsters. This approach has been successful with estimating the abundance of reef-associated fishes (e.g. Sale et al. 1984, McCormick and Choat 1987) and the stock of the spiny lobster *Panulirus argus* on the Bahama Banks (Smith and van Nierop 1986).

In this paper we describe how divers estimated the *Panulirus ornatus* stock in Torres Strait by counting lobsters in strip-transects. The study area was bounded in the west by 142°E, in the east by 142°57′E and the Warrior Reef complex, in the south by 10°52′S and Cape York, in the north by the Papua New Guinea coast (Fig. 1) and enclosed ~25 000 km$^2$ of potential lobster habitat.

## Pilot studies

Prior to attempting the full-scale stock survey, it was essential to assess its feasibility and determine the most effective sampling strategy by undertaking pilot studies in the area. These were done during mid-1988.

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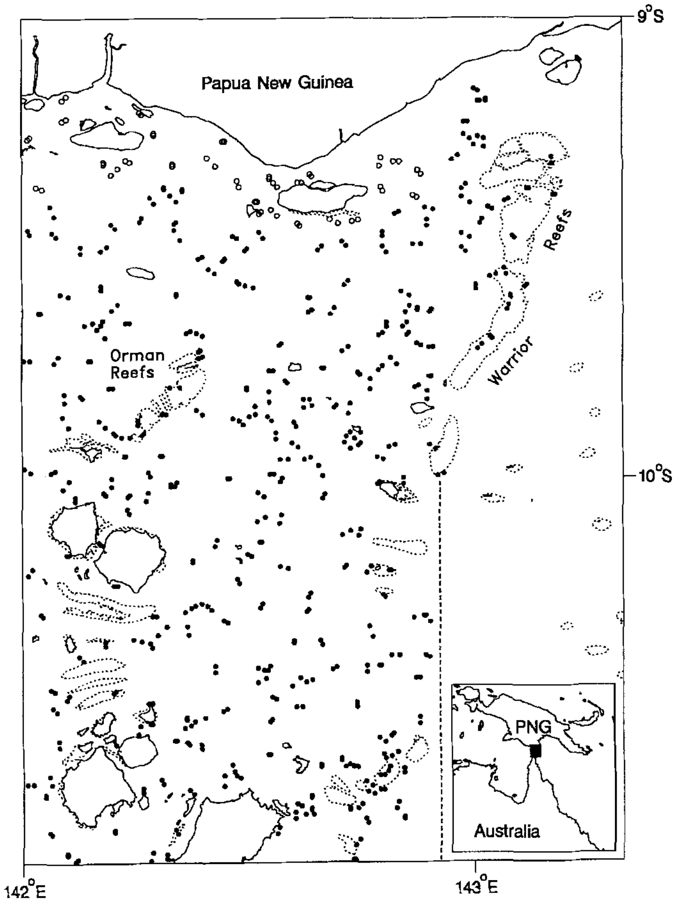


**Fig. 1.** Chart of Torres Strait showing survey area. Vertical dashed line indicates eastern boundary of survey area south of Warrior Reef complex, irregular continuous lines indicate coastline of mainland and islands, and irregular dotted lines, coral reefs. Small filled circles: positions of sampled transects; small open circles: transects not sampled in northernmost part of study area, near Papua New Guinea coast, due to bad weather

**Table 1.** Design of pilot study to optimize the sampling unit: three transect-width (m) × four transect-area ($m^2$) combinations were examined. Tabulated data are dimensions (m) of the transects; bottom line is replication of each transect size required to sample 6 000 $m^2$

| Transect width | Area ($m^2$) | | | |
|---|---|---|---|---|
| | 500 | 1 000 | 1 500 | 2 000 |
| 1 m | 1 × 500 | 1 × 1 000 | 1 × 1 500 | 1 × 2 000 |
| 2 m | 2 × 250 | 2 × 500 | 2 × 750 | 2 × 1 000 |
| 4 m | 4 × 125 | 4 × 250 | 4 × 375 | 4 × 500 |
| $n$/6 000 $m^2$ | 12 | 6 | 4 | 3 |

**Table 2.** Structure of second pilot survey, designed to assess source and amount of variation in *Panulirus ornatus* abundance. The three different spatial scales of sampling (locations, sites, and transects) were random and nested within the fixed factors region and habitat. Letters in parentheses refer to nesting of source factor within higher level factors

| Source | No. of levels | Description |
|---|---|---|
| Region | 2 | Orman Reefs and Warrior Reefs area |
| Habitat | 2 | Reef front and deep areas |
| Location (HR) | 3 | Random within habitat (H) and region (R) |
| Sites (LHR) | 3 | Random within each location (L) |
| Transects | 3 | Random within each site |
| Total | 108 | Replicates |

## Materials and methods

### *Sampling unit optimization*

The precision of abundance estimates can be affected by the area and shape of sampling units, depending on how the study organism is distributed in its environment (Andrew and Mapstone 1987). The width of transects is also important, as cryptic organisms become less visible with distance (Sale and Sharp 1983). Consequently, the effects of total transect area and transect width on the estimates of mean *Panulirus ornatus* abundance and precision ($p = \mathrm{SE}/\bar{x}$) were examined.

The procedure involved surveying 6000 $m^2$ of lobster fishing grounds with randomly placed transects of each of 12 combinations of transect area and width (Table 1). Thus, twelve 500 $m^2$, six 1000 $m^2$, four 1500 $m^2$, and three 2000 $m^2$ transects were required for each width (1, 2, and 4 m), totalling 75 transects for one replicate set of estimates of mean and variance for each of the 12 combinations of transect area and width. This procedure was repeated at three other randomly chosen locations within the fishing ground to give four replicate estimates of abundance and precision for analysis of variance. The time required to lay-out and census the transects of each type was also recorded.

### *Sampling design optimization*

It was also necessary to assess the level of variation at larger spatial scales of sampling because marine organisms are often patchily distributed at multiple spatial scales (Cochran 1977, Underwood 1981, Andrew and Mapstone 1987). In order to allocate appropriate replication among a range of spatial scales, a second pilot survey was carried out by counting lobsters in a total of 108 transects (Table 2) of the type that was found to be optimal in the first study (i.e., 4 × 500 m transect). Three transects were positioned ~0.5 km apart at each of 36 sites. The sites were distributed in groups of three about 2.5 km apart at each of 12 locations. Three locations were separated by ~10 km within each of two habitats and two regions of the fishery.

For each transect census, a 500 m-long line was laid onto the substratum from a dinghy. Two divers then swam down the line carrying a 2 m measuring rod and recording all lobsters within 2 m each side of the line. Because each diver was responsible for only a 2 m-wide strip, all ledges and crevices could be searched very thoroughly for cryptic lobsters. The times taken to survey each transect, site and location were recorded.

The pilot survey data were analysed using a hierarchical ANOVA procedure to estimate the variance in lobster abundance at each spatial scale of sampling (location, sites, and transects). Cost-benefit procedures (Underwood 1981), that take account of the relative variance and sampling time at each scale, were used to optimize the relative intensity of sampling among locations, sites, and transects. Further, because the relative level of variance within, and the areas of, each habitat differed, it was also important to determine the optimal proportional allocation of the total sampling effort among habitats (Cochran 1977, McCormick and Choat 1987). The areas of the habitats were estimated from topographic

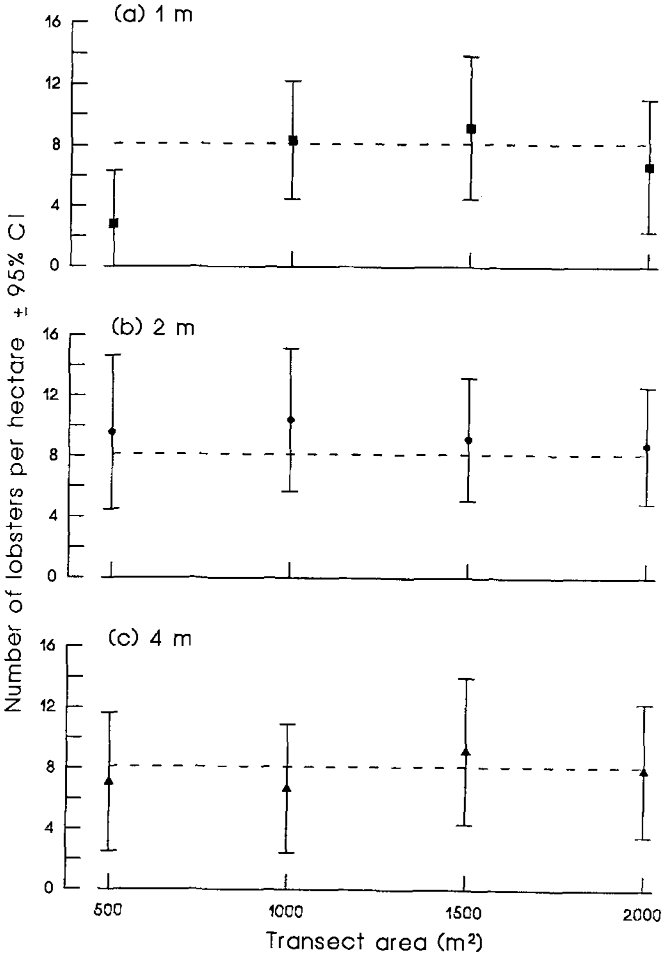


**Fig. 2.** *Panulirus ornatus*. Mean density in transects of three different widths and four different areas. Vertical bars represent 95% confidence intervals of means; horizontal dashed lines indicate overall mean density estimate for habitat sampled during first pilot study

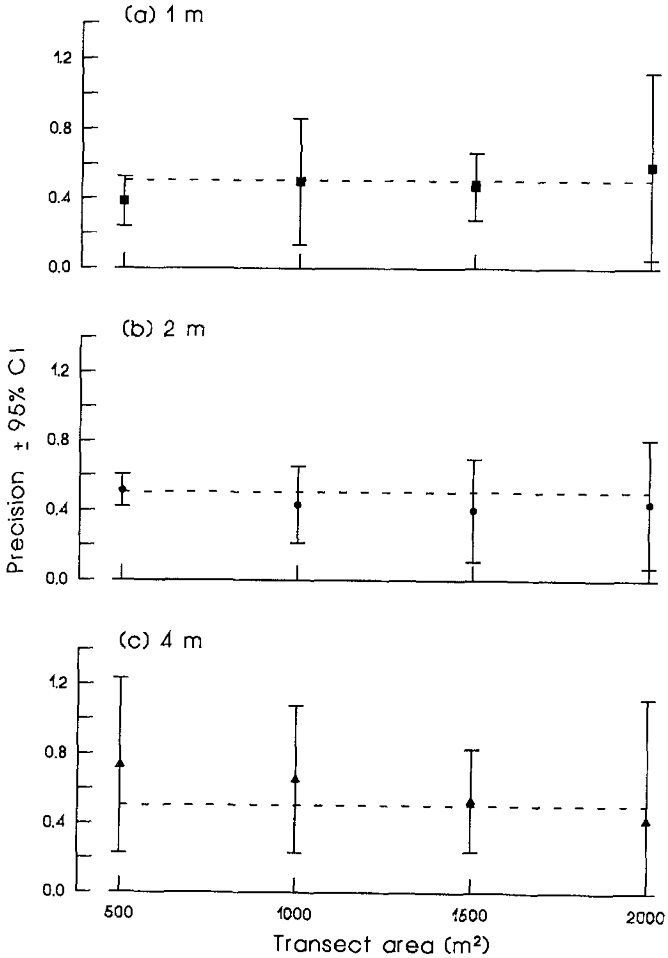


**Fig. 3.** *Panulirus ornatus*. Mean precision of density estimates in transects of three different widths and four different areas in the first pilot study. Other details as in legend to Fig. 2

charts; windward reef-slope areas covered ~1% of Torres Strait, shoal areas (submerged coral reef) covered ~9%, and the remaining area of deep water covered ~90%. The variances of lobster abundance in the reef slope and deep habitats were estimated by using separate ANOVA's of the pilot survey data for the two habitats and then re-calculating the variances obtained to take into account the optimal levels of replication at each sampling scale that were determined by the cost-benefit analysis. The variance estimate for the shoal areas was taken from ANOVA of the combined data from the other two habitats, as the shoal areas were considered to have a variance intermediate between the reef slope and deep habitats. The fraction of the total sampling effort (i.e., numbers of locations) to be allocated to each habitat was then calculated in proportion to the product of the variance and proportional area of each habitat.

The final objective of the pilot studies was to determine whether a full-scale survey was feasible; i.e., could the lobster stock be estimated with a sufficiently small confidence interval while keeping cost and field time within reasonable limits. This involved an iterative process of trialling different amounts of total sampling effort (i.e., numbers of locations) and estimating the likely variance ($SE^2$) and 95% confidence interval (95% CI) for each. This enabled an assessment of the trade-offs between the sampling effort and the level of confidence, and the identification of a suitable compromise.

## Results

### *Sampling unit optimization*

The mean and precision of *Panulirus ornatus* abundance estimates did not shown any particular trend with either different areas or widths of transects (mean: Fig. 2; precision: Fig. 3), although the 1 × 500 m transects tended to underestimate abundance relative to the average over all transects (Fig. 2). Analysis of variance confirmed the lack of significant effects. However, the estimate of the time required for sufficient replicates to attain a particular level of precision ($p = 0.10$) differed greatly among transect types. The largest and widest transect type (4 × 500 m) was most efficient (Fig. 4), and could be expected to provide the most precise abundance estimate for a given amount of field time or funds. Thus, 4 × 500 m transects were used in all subsequent studies.

*Sampling design optimization*

The level of variation in lobster abundance at the three spatial scales of sampling in the pilot survey, estimated by analysis of variance, are shown in Table 3 a. The negative value for variance associated with the site level indicated that sites should be dropped from the sampling strategy; the relative time-cost and variance associated with locations and transects indicated that the most efficient strategy for a full-scale study would be to do two transects at each location (Table 3 a). This changed sampling strategy required that the variances associated with each habitat be recalculated (Table 3 b) for optimal proportional allocation of the total sampling effort to each habitat. The deep habitat was the most variable and covered the largest area; thus, most of the sampling effort in a full-scale study should be allocated to this habitat (92%, from 5.420/5.862: Table 3 b). Conversely, the reef slope was the least variable, covered the smallest area, and should be allocated the least effort (1%, from 0.029/5.862: Table 3 b). The shoal habitat was intermediate and should be allocated about 7% of the effort (from 0.413/5.862: Table 3 b).

A feasible compromise between the level of confidence of the lobster-stock estimate and the total effort required to obtain it was considered to exist when a suitably small variance ($SE^2 = 0.0572$), which corresponded to a 95% CI of ±10% of the mean number of lobsters per transect in the pilot stock survey, was predicted to be obtained with a total sampling effort of 300 locations (Table 3). However, the average density of lobsters in a full-scale survey was likely to be less than in the pilot survey, which was undertaken within the main fishing grounds; consequently, it was expected that the 95% CI would be somewhat greater than ±10%. Nevertheless, the surveying of 300 locations was estimated to require at least 6 wk of field time, which was a reasonable upper limit to the field commitment.

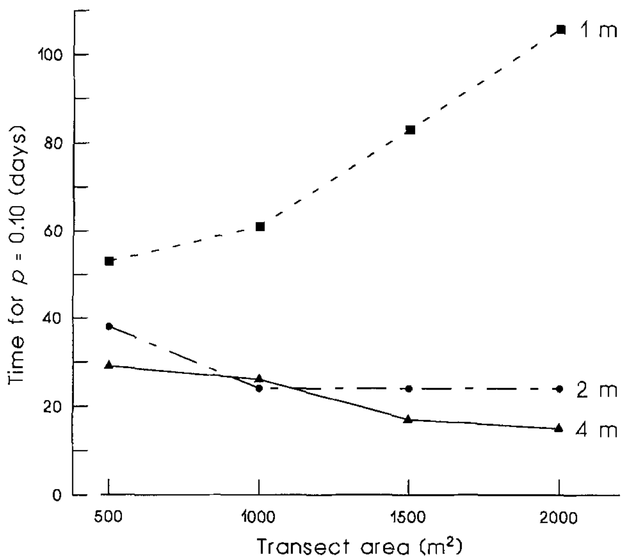


**Fig. 4.** *Panulirus ornatus*. Total sampling time (days) required to achieve precision of $p = 0.10$ for density estimates from transects of three different widths and four different areas

## Full-scale stock survey

The pilot surveys and optimization of the sampling strategy showed that a full-scale survey was feasible; i.e. a sufficiently precise estimate of lobster abundance was obtainable within budgetary and field-time constraints.

**Table 3.** Procedure for optimal allocation of sampling effort to (a) different spatial scales according to variance and time cost at each scale, and (b) different habitats according to proportional area and recalculated variance estimate of each habitat. Total number of locations was determined by amount of replication required to give a variance small enough for a 95% CI of ±10% of mean density of *Panulirus ornatus* in the pilot survey. MS: mean-square from ANOVA; $l$, $s$, $t$: number of locations, sites, transects; $_l$, $_s$, $_t$: subscript identifiers for variables relating to locations, sites, transects; $s^2$: sample variance; $c$: time cost; $W_h$: proportional area of strata; $n_h$: number of locations per stratum; $s_{\bar{x}_{strat}}$: standard error of overall stratified mean

**(a) Cost-benefit analysis**

| Source | $s^2$ | | $c$ (h) |
|---|---|---|---|
| Location | $s_l^2 = (MS_l - MS_s)s \cdot t =$ | 3.46 | 0.80 |
| Sites | $s_s^2 = (MS_s - MS_t)t$ | $= -1.47$ | 0.10 |
| Transects | $s_t^2 = MS_t$ | $=$ 14.06 | 0.85 |

$$\text{Transects/location} = \sqrt{(c_l \cdot s_t^2)/(c_t \cdot s_l^2)} = \sqrt{(0.80 \times 14.06)/(0.85 \times 3.46)} = 1.96 \Rightarrow 2$$

**(b) Re-calculation of $s_h^2$, optimal allocation and estimation of sample size**

| Strata | $s_t^2 + t \cdot s_s^2 + s \cdot t \cdot s_l^2$ | $= s_h^2$ | $W_h$ | $W_h \cdot s_h$ | $n_h$ | $W_h^2 \cdot s_h^2/2n_h$ |
|---|---|---|---|---|---|---|
| Slope | 8.17+2×1.28+1×2×0 | = 10.7 | 0.009 | 0.029 | 2 | 0.0002 |
| Shoal | 14.1 +2×0 +1×2×3.46 | = 20.9 | 0.090 | 0.413 | 21 | 0.0041 |
| Deep | 19.9 +2×0 +1×2×8.10 | = 36.2 | 0.901 | 5.420 | 277 | 0.0529 |
| | | | | 5.862 | 300 | 0.0572 |

Estimated 95% confidence interval for 300 locations (600 transects)

$$95\%\ CI_{(est)} = \pm t_{0.05} \cdot s_{\bar{x}_{strat}} = \pm 1.964\sqrt{0.0572} = \pm 0.469 \Rightarrow \pm 10.8\%$$

## Materials and methods

### *Habitat classification and stratification*

Satellite imagery (Landsat MSS data) together with the MicroBRIAN image-analysis software was used for detailed mapping of Torres Strait and classification of the study area into seven image-classes (e.g. Kuchler et al. 1986). This procedure accurately identified the position and determined the areas of the three habitat strata (windward reef slope, shoal areas = submerged coral reef, and areas too deep to subdivide further using this method). In addition, several shallow habitats unsuitable for lobsters (e.g. sand and rubble banks, reef pavement) were identified and eliminated from the survey.

The deep stratum actually combined several types of habitat and the density of *Panulirus ornatus* varied greatly among them. In order to reduce the overall variance caused by the different habitat types within the deep stratum, an additional five strata within the deep stratum were defined based on habitat data gathered during the survey (i.e., >50% rock, 10 to 50% rock, <10% rock+rubble, sand, and silt+mud), and these additional strate were included in the analysis. The areas of the five additional strata were estimated from the total area of the deep strata according to the proportion of transects in each of the additional classifications. Obviously, transects were not allocated optimally among these strata, as the variance and area data were not available until after the survey was completed.

The position of all transects was mapped prior to the field phase of the survey to avoid subjective and possibly biased positioning. The entire survey area was divided into 3 × 3 km locations; this size was chosen so that the number of locations to be sampled (300) formed only about one-tenth of the total number of possible locations (~2650), thus finite-population-correction of the variances was avoided (Cochran 1977). The 300 locations were allocated in close proportion to the known areas and estimated variances of the habitat strata, and at random within each stratum. The coordinates of the beginning of each of the two transects within each 9 $km^2$ location were selected at random from a 0.5 km reference grid. The distribution of these transect pairs is shown in Fig. 1.

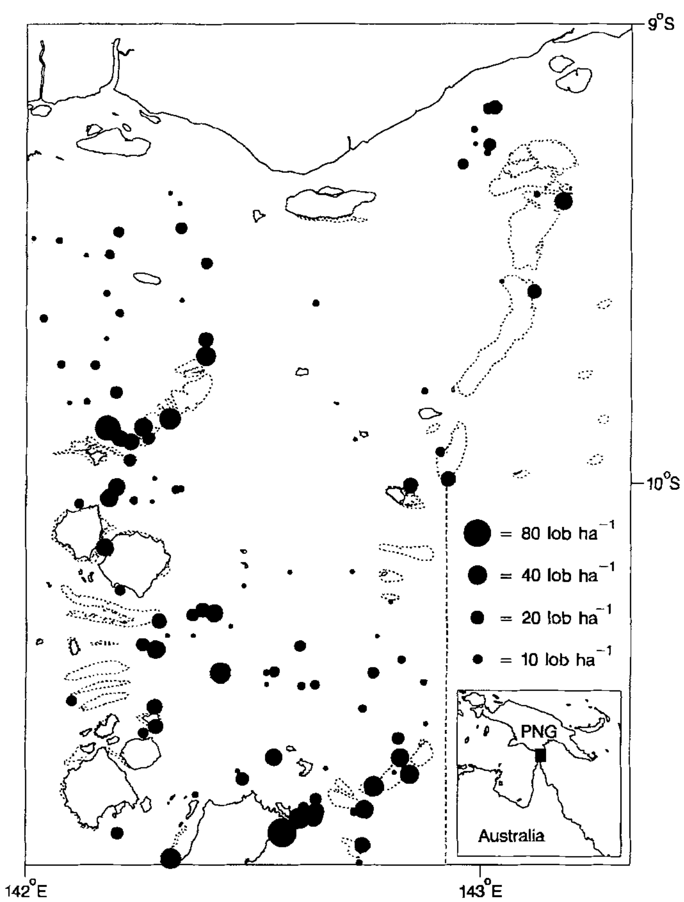


**Fig. 5.** *Panulirus ornatus*. Chart of Torres Strait showing density at sampled locations. Area of filled circles is proportional to density of lobsters (examples are given in key); highest density sampled was 90 lobsters $ha^{-1}$ (largest circle on chart), lowest non-zero density was 2.5 lobsters $ha^{-1}$ (smallest circles)

### *Main transect survey*

The full-scale survey of Torres Strait in May-June 1989 took ~7 wk, with three teams of divers, each operating from a dinghy. Two teams counted lobsters while the third team, which included a professional lobster spear-fisherman, sampled the surveyed population for size measurements. The previously mapped starting point of each transect was located with a combination of GPS-satellite fixes and radar position fixes from the support vessel, or multiple compass bearings. The 500 m transect line was then deployed and paired divers recorded the number of lobsters within the 4 m width of the transect. The amount of seagrass and epibiota, the number of other animals (including pearl shell), and the substratum type were also recorded. Most locations were sampled successfully; however, towards the end of the survey, high rainfall over Papua New Guinea increased the flow of turbid water from rivers, and very strong winds mixed seabed sediments into the water column. As visibility was reduced to zero, 29 locations close to the Papua New Guinea coast and the area they represented (~1500 $km^2$) had to be deleted from the survey (Fig. 1).

The data on lobster numbers per transect were separated into their respective strata and the abundance estimate for the entire study area was calculated as the sum of the products of the mean number of lobsters per transect and the total number of transects within each stratum. The variance of each habitat stratum was calculated using nested analysis of variance of the lobster counts in transects at each location. The variance (actually $SE^2$) of the overall abundance estimate was derived from the summation of the products of the variance of each strata and the square of the proportional area of each strata divided by the the number of transects (=2 × *n* locations) in each strata.

### *Lobster biomass estimate*

The professional lobster spearfisherman speared all lobsters as they were encountered to minimize bias. The samples from each location were weighed, measured and sexed, so that size-frequency distributions of the population could be determined and the abundance estimate could be converted to a stock estimate by weight. Samples of the commercial catch in June 1989 were also measured to compare with the surveyed population. The year-class components in the size-frequency distributions were separated using "mix analysis"(Macdonald and Pitcher 1979).

## Results

### *Lobster abundance*

*Panulirus ornatus* were observed in 107 of the 271 locations that were sampled, and most were found in the southern and western regions of the survey area (Fig. 5). The density estimates of lobsters in these locations ranged from 2.5 to 90 lobsters per hectare (Fig. 5). The highest densities of lobsters were associated with the windward reef slope and rocky strata in deeper water. In contrast, the density was virtually zero in the middle part

**Table 4.** *Panulirus ornatus.* Calculation of population size and variance estimates for Torres Strait study area from analysis of variance of transect survey data, and estimation of stock biomass and 95% CI from number and mean weight of legal-sized tails in population. $N_h$: total number of possible transects in each stratum; $\bar{x}_h$: stratum mean; other symbols as in Table 3

| Strata | Area | $W_h$ | $N_h$ | $n_h$ | $\bar{x}_h$ | $s_h^2$ | $W_h^2 s_h^2/2n_h$ | $N_h \bar{x}_h$ |
|---|---|---|---|---|---|---|---|---|
| Slope | 228 | 0.0105 | 114 000 | 5 | 3.80 | 12.65 | 0.0001 | 433 200 |
| Shoal | 1 009 | 0.0463 | 504 500 | 10 | 0.05 | 0.05 | 0.0000 | 25 225 |
| <50% rock | 884 | 0.0405 | 442 000 | 11 | 3.73 | 14.84 | 0.0011 | 1 648 660 |
| 10–50% rock | 2 892 | 0.1326 | 1 446 000 | 36 | 3.82 | 34.75 | 0.0085 | 5 523 720 |
| <10% rock, rubble | 7 150 | 0.3279 | 3 575 000 | 89 | 1.46 | 9.43 | 0.0057 | 5 201 625 |
| Sand | 8 195 | 0.3759 | 4 097 000 | 102 | 0.30 | 4.43 | 0.0031 | 1 245 640 |
| Silt + mud | 1 446 | 0.0663 | 723 000 | 18 | 0.00 | 0.00 | 0.0000 | 0 |
| | 21 804 | 1.0000 | 10 902 000 | 271 | | | 0.0185 | 14 078 070 |

Standard error: $s_{\bar{x}_{strat}} = \sqrt{0.0185} = 0.1359$

95% CI: $\pm t_{0.05} \cdot N \cdot s_{\bar{x}_{strat}} = \pm 1.964 \times 10\,902\,000 \times 0.1359 = \pm 2\,910\,000$

Population estimate: $X = 14\,000\,000 \pm 20.7\%$

Stock estimate: ($\bar{x}$ tail weight = 346 g) = 2 776 t

Confidence interval: 2 200 – 3 350 t

of the northern half of the study area where the substratum was fine sand and silt. Overall, the five additional strata, based on hardness of the substratum, within the deep area accounted for 25% of the variance in density of lobsters. The density of the epibenthic macrofauna (sponges, hard, horny, and soft corals) also varied with the hardness of the substratum, and division of the deep areas into four strata based on the amount of macrofauna accounted for ~23% of the variance in lobster density. Together, the substratum and macrofauna accounted for ~26% of the variance. The shoal areas, as classified by the image analysis, were shallower than expected and did not include the coralline habitats up to 3 m depth as had been expected. Consequently, much of the latter reef habitat was subsumed into the deep strata, and very low numbers of lobsters were seen in the shoal strata.

The estimates of lobster density per transect for each stratum, when expanded to give an abundance estimate for each stratum and then summed, yielded a population estimate for the survey area of ~14 million lobsters (Table 4). The variance of the overall abundance estimate, calculated from the variance, proportional area and sampling effort whithin each strata (Table 4), was $SE^2 = 0.0185$ which corresponded to a 95% CI of 2.9 million, or ±21% of the lobster population estimate. The precision of the estimate ($p$: $SE/\bar{x} = 0.105$) was relatively high for a large-scale ecological study.

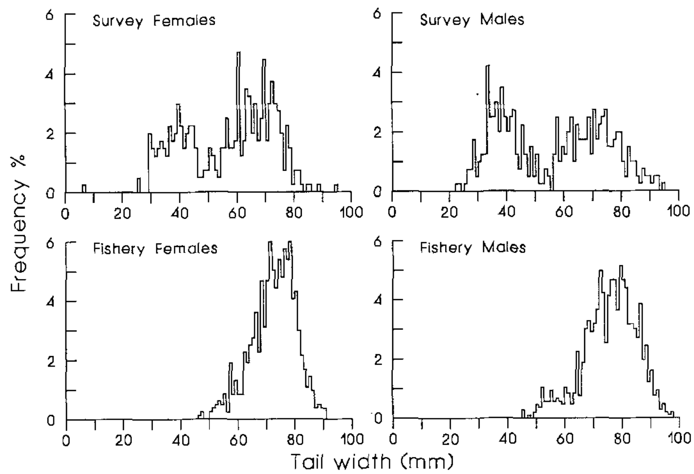


**Fig. 6.** *Panulirus ornatus.* Size-frequency distribution of females and males sampled during survey and in the catch of the fishery in June 1989. Legal minimum size corresponds to tail width of ~52 mm

### *Lobster biomass estimate*

The size-frequency distribution of the lobsters sampled by the professional fisherman (Fig. 6) showed two distinct modes: the left mode comprised the 1+ year-class and made up 41% of the population, the right mode comprised the 2+ and 3+ year-classes, which made up 57% and ~2% of the population respectively (from "Mix analysis"). Lobsters less than the legal size (i.e., 100 mm tail length, ~52 mm tail width) would have been almost entirely from the 1+ year-class and made up 43% of the population. Lobsters greater than the legal size accounted for 57%, and their average tail weight was 346 g. Thus, the estimate of the stock of legal-sized lobsters in the study area was 6.4 to 9.7 million, or between 2 200 and 3 350 t tail weight.

The size-frequency distribution of several thousand lobsters from the June 1989 commerical catch differed greatly from that of the survey (Fig. 6). The 1+ year-class was absent from the fishery sample, obviously because almost all 1+ lobsters are less than the legal size in June. Nevertheless, the fishermen also target larger lobsters from the 2+ and 3+ year-classes, such that, in the year of the survey, lobsters ≲70 mm tail width were not fully recruited to the fishery; in other years, this size could vary as growth rates vary among years. The average weight of lobster tails brought to processors in June was 410 g, although it would be ~10% less over the whole year, and the annual catch averaged over the last 5 yr was 250 t of tails; thus, ~700 000 lobsters are caught each year. The total number of lobsters in each size class of the

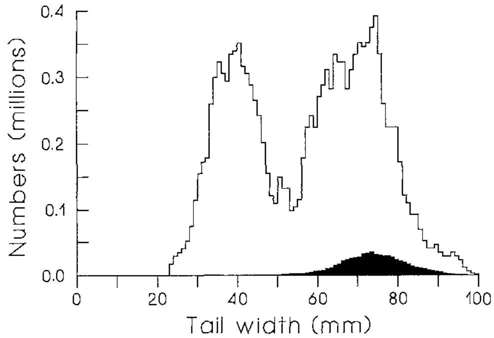


**Fig. 7.** *Panulirus ornatus.* Approximate total numbers of each size class in population estimated from present survey (open area) and in annual catch of fishery (filled area)

catch can be compared with the estimated numbers in the population (Fig. 7) to give an estimate of the fishing mortality coefficient ($F$) for each class. $F$ is practically zero for lobsters $<52$ mm tail width, and although $F$ increases with size $>52$ mm, until it reaches a maximum and levels off at $>70$ mm, it is clear that $F$ is small for all size classes (overall $F \approx 0.1$).

## Discussion

This study has demonstrated the value of visual transect sampling, a method not used often in fisheries research, for estimating the abundance of a commercially important species. The value of doing pilot surveys to optimize the sampling design is also clear. Considerable gains in efficiency (up to 600%) were made by calculating the time required to achieve a given level of precision with different types of transect. The cost-benefit analysis indicated levels of replication at various spatial scales that were ~60% more efficient than those in the pilot design. The stratification of sampling among the different habitats produced gains in efficiency of about 15 to 20%. Often the gains from stratification would be larger (70 to 1500%, McCormick and Choat 1987) particularly when the study species is a habitat specialist, unlike *Panulirus ornatus*, which has broad habitat requirements. It was estimated that if the mean and variance of lobster numbers, and approximate areas of the five substrata within the deep habitat had been known prior to the full-scale survey, further gains in efficiency of ~15% could have been achieved, with optimal allocation of sampling units among these deep substrata.

Although transect area and width had no apparent effect on sampling efficiency in the pilot study, they often would and should be assessed (Andrew and Mapstone 1987). We deliberately avoided the error resulting from decreasing visibility of cryptic organisms with transect width, by having two divers swim each transect, each responsible for only a 2 m strip. Even in poor visibility, the divers could see all lobsters without deviating from the centre of the strip. Thus, the 12 transect area/width combinations were examined primarily to determine the combination best suited to the patchiness of lobsters; the lack of effect occurred possibly because all combinations included several smaller scales of patchiness.

With larger sample sizes and more detailed habitat stratification, it would be possible to achieve even greater precision. However, the trade-offs between precision and sampling effort are nonlinear (Bros and Cowell 1987). For example, halving the 95% CI to ±10% would require at least four-fold more locations (~1100) to be sampled. This amount of effort would be difficult to justify given that over-exploitation would not be considered a problem until the stock had been reduced to significantly less than 50% of virgin levels (probably $<<1500$ t). This survey was more than adequate for this purpose; in fact it was sufficiently precise to detect a 20% decrease in abundance (i.e., to $\leq 2200$ t). In contrast, many estimates of stock size have very wide confidence intervals, especially those derived from tagging studies (Gulland 1983), partly as a result of a magnitude of the problem. Using similar transect methods, Smith and van Nierop (1986) estimated the abundance of *Panulirus argus* on the 60 000 $km^2$ area of the Bahama Banks, with 95% CIs of 80 to 120%, and McCormick and Choat (1987) estimated the size of the *Cheilodactylus spectabilis* population in a 1.5 $km^2$ marine reserve and in a 1 $km^2$ area of adjacent coastal habitat with ±16 and ±28% confidence, respectively.

Potential sources of bias with transect methods include the cryptic behaviour of lobsters, underwater visibility, ruggedness of the substratum, and differences in the divers' abilities to detect lobsters. However, we consider that the accuracy of the census was likely to be high for four main reasons. (1) The divers searched a narrow path intensively, using 2 m measures to delimit the width accurately, so that counts in even cavernous habitat or turbid water should not have seriously underestimated abundance. (2) The substratum of scattered small rocks, rubble and sand that supported about 97% of the population did not provide cavernous dens. Consequently, lobsters were not well concealed – their antennae and carapace generally being clearly visible. (3) The rugged coral reef slope habitat, where the chances of under-counting would be highest, comprised only about 1% of the survey area; even if divers undercounted by as much as 50% in this habitat, the final stock estimate would be in error by only $<1.5$%. (4) Different divers' counts, adjusted for differences among strata, did not differ significantly ($MS_{div} = 2.59$, $F = 1.03$ [7,1036], $P = 0.41$). Had there been any bias, the stock would have been underestimated only slightly, which is preferable to an overestimation.

The standing stock per unit area of legal-sized *Panulirus ornatus* in Torres Strait (~375 $kg/km^2$ whole weight) is comparable to the range of estimates made by many workers for *P. argus* in the tropical Western Atlantic (83 to 583 $kg/km^2$; references in Smith and van Nierop 1986). The wide range of estimates for *P. argus* may result partly from different workers sampling different subsets of a wide range of habitats that support the species. For example, if we had sampled only the habitat in the main fishing grounds in Torres Strait, our stock per unit area estimate would have been ~1100 $kg/km^2$ whole weight.

A precise estimate of abundance or biomass provides the opportunity to apply several methods of assessing the fishery. For example, a preliminary estimate of the maximum sustainable yield (MSY) can be obtained using simple models designed for data-limited situations. Cadima's estimator (in Troadec 1977) requires estimates of only natural mortality, biomass and current catch. Smith and van Nierop (1986) used this model to estimate the MSY of *Panulirus argus* on the Great and Little Bahama Banks (155 and 257 kg/km$^2$, respectively). However, Garcia et al. (1989) pointed out that Cadima's estimator was theoretically inconsistent and derived some more robust alternative models. Nevertheless, Garcia et al. stressed the frailty of their simple models in terms of their reliability to predict sustainable yields. The simple models also assume that fishing mortality at MSY ($F_{MSY}$) is equal to natural mortality ($M$), although it is widely considered that $F_{MSY}$ is usually less than $M$ – in some cases as small as $F_{MSY} \approx 0.6\ M$ (Gulland 1983, Garcia et al. 1989). Consequently, we used values from $F_{MSY} = 0.6\ M$ to $E_{MSY} = 1.0\ M$ in models derived by Garcia et al. Further, as the value of $M$ for *P. ornatus* was not known, a range of $M$-estimates derived from other tropical *Panulirus* species (Olsen and Koblic 1975, Munro 1983, Ebert and Ford 1986) was substituted. Using this range of values of $M$ (0.4 to 0.9), the current catch ($\sim$250 t), and the biomass estimate from the survey (2200 to 3350 t), the potential yield of *P. ornatus* in the study area was estimated at between 310 and 1200 t, the mode being about 630 t.

The first approximation to the possible yield to Torres Strait corresponds to a production estimate per unit area of $\sim$40–160 kg/km$^2$ whole weight per annum (or 120 to 480 kg/km$^2$ whole weight in the main fishing grounds). In comparison, the potential yields of *Panulirus argus*, tabled from several workers by Smith and van Nierop (1986), range from 25 to 890 kg/km$^2$. Thus, it appears that the per unit area productivity of the *P. ornatus* stock may be comparable to that of the much larger tropical Western Atlantic *P. argus* fishery.

The current annual catch of *Panulirus ornatus* ($\sim$250 t tail weight) is approaching the lower of the MSY estimates, which suggests that the fishery is unlikely to be under threat at present and may even support greater effort. However, the limitations of the simple models should be kept in mind; in addition, there are several reasons why theoretical MSY may not be attained (Doubleday 1976, Marchesseault et al. 1976, Sissenwine 1976). Future research will be directed to producing more reliable estimates of sustainable catch and will build on the rigorous estimate of lobster abundance provided by the visual transect method and sampling optimization in this study.

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# Fishery-independent surveys and stock assessment of *Panulirus ornatus* in Torres Strait

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**Abstract.** The Torres Strait lobster fishery differs culturally and ecologically from other Australian lobster fisheries. Ornate rock lobsters (*Panulirus ornatus*) have been fished by the inhabitants of Torres Strait for centuries, and commercial fishing began in the late 1960s. The fishery is a major source of income for Torres Strait Islanders, and the aim of management is to balance the needs of traditional and commercial users under a treaty between Australia and Papua New Guinea. In 1989, the absolute abundance of lobsters in the main fishing grounds was estimated by a visual census and a simple assessment was made. Since then, annual fishery-independent surveys of the relative stock abundance, and catch sampling, have contributed to the development of a simple cohort dynamics model of the fishery; for a range of fishing mortalities, it estimates the potential yield and percentage escapement and has provided annual assessments of the status of the stock and potential yield one year in advance—information valuable for managers considering development options and negotiating catch-sharing agreements and access rights. Future research will develop the model by incorporating information from ongoing surveys, catch recording, and logbook data from the Australian and Papua New Guinean fisheries.

## Introduction

The Torres Strait *Panulirus ornatus* fishery contrasts strongly with other commercial lobster fisheries in Australia and many other major lobster fisheries in the world. These contrasts are in the ecology of the stock and the nature of the fishery, and they mean that different techniques are required for the data collection and stock assessment described in this paper.

### *The fishery*

Ornate rock lobsters have been fished by the traditional inhabitants of Torres Strait, probably for several centuries, and commercial fishing began in the late 1960s. Commercial involvement in the fishery developed gradually, and now there are about 24 small freezer boats (see Channells *et al.* 1987 for history). Independent involvement of Torres Strait Islanders in the fishery has also increased, with 300–500 dinghies now in use, and it has become a major source of income for them (Pitcher and Bishop 1995). Most commercial fishing for lobster occurs in Torres Strait, with some occurring along the far north-eastern coast of Queensland.

*Panulirus ornatus* individuals will not enter pots, so they are speared by divers fishing from dinghies. Divers using hookah compressors fish in deep grounds (5–25 m) between reefs, whereas free divers fish on reefs in shallow waters. Peak catches occur during February–July, and low effort during October–December separates the fishing seasons (Pitcher and Bishop 1995).

Annual catches during the 1990s have averaged about 200 t tail weight (Table 1). The landed value of the catch is $A5–7 million, and most is exported. The combined catch of divers from Australia and from Papua New Guinea (PNG; data from the PNG National Fisheries Authority, or NFA) is about 300 t.

The numbers of fishers, boats, and days and hours worked have increased substantially since the fishery began, though total effort is unknown (Pitcher and Bishop 1995). At the same time, the catch per hour has decreased to roughly one-half that recorded in 1974 (Channells *et al.* 1987). Hence, there is a continuing need for monitoring and assessment of the lobster stocks to provide advice on stock status.

The Australian Fisheries Management Authority (AFMA) has introduced limited entry, a minimum size limit of 100 mm tail length (~75 mm carapace length), catch-sharing arrangements with PNG that permit a specified number of dinghies to fish in Australian waters, and an annual two-month ban (October and November) on the use of hookah compressors (Pitcher and Bishop 1995).

### *Life history*

The life history of *Panulirus ornatus* in Torres Strait has some remarkable differences from that typical of tropical spiny lobsters (Pitcher *et al.* 1995). Torres Strait lobsters appear to grow significantly faster than do similar species, recruiting into the fishery about one year after settlement, at 100 mm tail length. The juvenile lobsters are fished for only

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**Table 1. Annual catch of the Australian diver fishery (AFMA records), survey count data and proportions of 1+ and 2+ cohorts, estimates of total population and cohort abundances, mean tail width of each cohort, estimates of total mortality rate ($Z$) and fishing mortality rate ($F_{expl.}$, $F_{YPR}$, $F_{YPR/Z}$ from three methods—see text), and estimates of potential yield (at $F$ = 0.4) as derived from the current stock assessment model with $M$ = 0.8**

| Year | Catch | Survey | | | Population | | | Tail width | | Mortality | | | | Yield |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (tails, t) | Total count | 1+ (%) | 2+ (%) | Total (million) | 1+ (million) | 2+ (million) | 1+ | 2+ | $Z$ | $F_{expl.}$ | $F_{YPR}$ | $F_{YPR\|Z}$ | (t) |
| 1978 | 119 | | | | | | | | | | | | | |
| 1979 | 124 | | | | | | | | | | | | | |
| 1980 | 124 | | | | | | | | | | | | | |
| 1981 | 150 | | | | | | | | | | | | | |
| 1982 | 193 | | | | | | | | | | | | | |
| 1983 | 122 | | | | | | | | | | | | | |
| 1984 | 130 | | | | | | | | | | | | | |
| 1985 | 207 | | | | | | | | | | | | | |
| 1986 | 349 | | | | | | | | | | | | | |
| 1987 | 242 | | | | | | | | | | | | | |
| 1988 | 216 | | | | | | | | | | | | | |
| 1989 | 243 | 1086 | 40.7 | 59.3 | 14.10 | 5.74 | 8.36 | 37.7 | 68.0 | | 0.13 | | | >800 |
| 1990 | 183 | 759 | 60.7 | 39.3 | 9.86 | 5.99 | 3.87 | 37.8 | 63.5 | 0.39 | 0.22 | 0.29 | 0.15 | 240 |
| 1991 | 166 | 811 | 78.9 | 21.1 | 10.54 | 8.32 | 2.22 | 40.0 | 66.5 | 0.99 | 0.32 | 0.25 | 0.23 | 250 |
| 1992 | 158 | 995 | 67.1 | 32.9 | 12.93 | 8.68 | 4.25 | 42.4 | 68.9 | 0.67 | 0.25 | 0.16 | 0.12 | 350 |
| 1993 | 189 | 491 | 74.9 | 25.1 | 6.38 | 4.78 | 1.60 | 42.7 | 71.6 | 1.69 | 0.54 | 0.19 | 0.33 | 365 |
| 1994 | 216 | 778 | 83.0 | 17.0 | 10.11 | 8.39 | 1.72 | 42.2 | 68.1 | 1.02 | 0.49 | 0.46 | 0.37 | 200 |
| 1995 | 208 | 603 | 72.5 | 27.5 | 7.84 | 5.68 | 2.16 | 41.9 | 68.1 | 1.36 | 0.49 | 0.22 | 0.29 | 350 |
| 1996 | 218 | 568 | 81.2 | 18.8 | 7.38 | 5.99 | 1.39 | 36.1 | 61.1 | 1.41 | 0.91 | 0.38 | 0.43 | 240 |
| 1997 | | | | | | | 1.82 | | | | | | | 250 |

one year (Skewes *et al.* 1994) before most emigrate to breeding grounds in spring each year, when catch rates decline markedly. Tagging showed that emigrating lobsters moved north-east into the Gulf of Papua, maturing at the same time (Moore and MacFarlane 1984; Bell *et al.* 1987). Some lobsters migrated >500 km to coastal reefs in the eastern Gulf of Papua (MacFarlane and Moore 1986). Lobsters on these Papuan reefs were in very poor physiological condition (Trendall and Prescott 1989), and virtually all died after the breeding season (Dennis *et al.* 1992). Such catastrophic mortality is very unusual for lobsters; most species can live and breed for many years.

Until recently, the reefs in the eastern Gulf of Papua were the only known significant breeding grounds. Recent surveys with a small research submarine showed that there may be other lobster breeding grounds in the far northern Great Barrier Reef (Prescott and Pitcher 1991). The significance of this breeding ground and the mortality of lobsters there have yet to be confirmed (Pitcher *et al.* 1995).

### *Stock boundaries*

*Panulirus ornatus* has an Indo-West Pacific distribution. In Australian waters, it occurs across the tropical north but is most abundant in Torres Strait and along the far north-eastern coast of Queensland (Pitcher 1993). From the perspective of fisheries assessment, the stock probably comprises all lobsters north of 14°S along the Queensland coast, in Torres Strait, and off the south-eastern coast of PNG—any breeding within this region could potentially supply recruits to all areas within the region because of a clockwise gyre in the north-western Coral Sea (Pitcher *et al.* 1995). This supposition was supported by electrophoretic studies (Salini *et al.* 1986) that showed negligible genetic variation within this region.

### *The first assessment*

The first, preliminary, stock assessment was made possible by an estimate of the number of lobsters in the ~25 000-km$^2$ area of the Torres Strait fishing grounds, including PNG, in 1989 (Pitcher *et al.* 1992*a*). This was done by visual-transect survey methods, with divers counting lobsters at almost 600 sites. The population size was estimated to be  million lobsters (95% confidence interval), including recruiting 1+ and recruited 2+ cohorts. The number of legal-sized lobsters was about 9 million, with a biomass of 2200–3350 t tail weight. Comparison with the catch ($C$) in the same year (243 t, plus 70 t for PNG; NFA data) indicated that exploitation, $u$, was low ($u = C/B \approx 0.12$). The key stock-size parameter (approximately equivalent to unexploited biomass $B_0$, given the low value of $u$) initially permitted a rule-of-thumb model of maximum sustainable yield ($MSY$) to be applied:

$$[MSY] = \tfrac{1}{2}MB_0$$

(Gulland 1983). In 1989, the rate of natural mortality ($M$) was unknown, so estimates for similar tropical species were substituted (e.g. $M \approx 0.5$), giving a $Y_{MS}$ estimate of just over 600 t tails. The 1989 catch was about half this $Y_{MS}$ estimate, suggesting that fishing mortality ($F$) was low. The assessment was considered conservative because lobsters outside the survey area were not included.

AFMA requested that stock assessments be continued, to underpin the primary management objective of conserving the stock for optimal use and to fulfil the AFMA requirement for annual reporting of stock status for the fisheries under its jurisdiction. This paper describes the collection of research data and the stock assessment techniques, results and implications.

## Annual fishery-independent surveys

We conducted fishery-independent surveys of lobsters in the Australian Torres Strait each year since the 1989 survey. These surveys provided an annual index of the relative abundances of the two year-classes (1+ and 2+) in the Torres Strait population, and estimates of growth and mortality. The Islander catch and catch rate were also monitored.

### *Methods*

Of the original 572 sites surveyed in 1989, a subset of 100 sites (Fig. 1) was chosen that had the highest densities of lobsters. This subset accounted for 86% of lobsters observed in Australian waters during the 1989 survey, and the size distribution of lobsters from the subset was assumed not to differ from that of lobsters sampled at all sites.

The annual surveys were conducted in June–July, when the 1+ lobsters were large enough to be conspicuous but before they recruited. The fixed transect starting points were accurately relocated each year with GPS. Paired divers counted and sampled lobsters during 20-min (bottom time) dives, directed with the current. Any lobsters not successfully sampled were noted for size (1+ or 2+ misses). The tail width, sex and moult stage of each sampled lobster were measured. Habitat types were also recorded, by methods described in Pitcher *et al.* (1992*b*).

In 1996, the number of sites was reduced to 82 because of cost rationalization—the sites omitted accounted for about 7% of the lobsters observed during previous surveys. The total counts for 1996 were rescaled to estimate counts per 100 sites, based on a regression between counts for the 82 and 100 sites for the years 1990–95 ($r^2 = 0.991$).

The catch by Islanders fishing in the central-western islands was also surveyed at the same time as the research survey. The data recorded included: catch weight (tails only) for each fisher, hours worked by each fisher, number of divers per dinghy, fishing method used (free-diving or hookah), and the width, sex and moult stage of each tail.

The data on tail size distribution were analysed with the

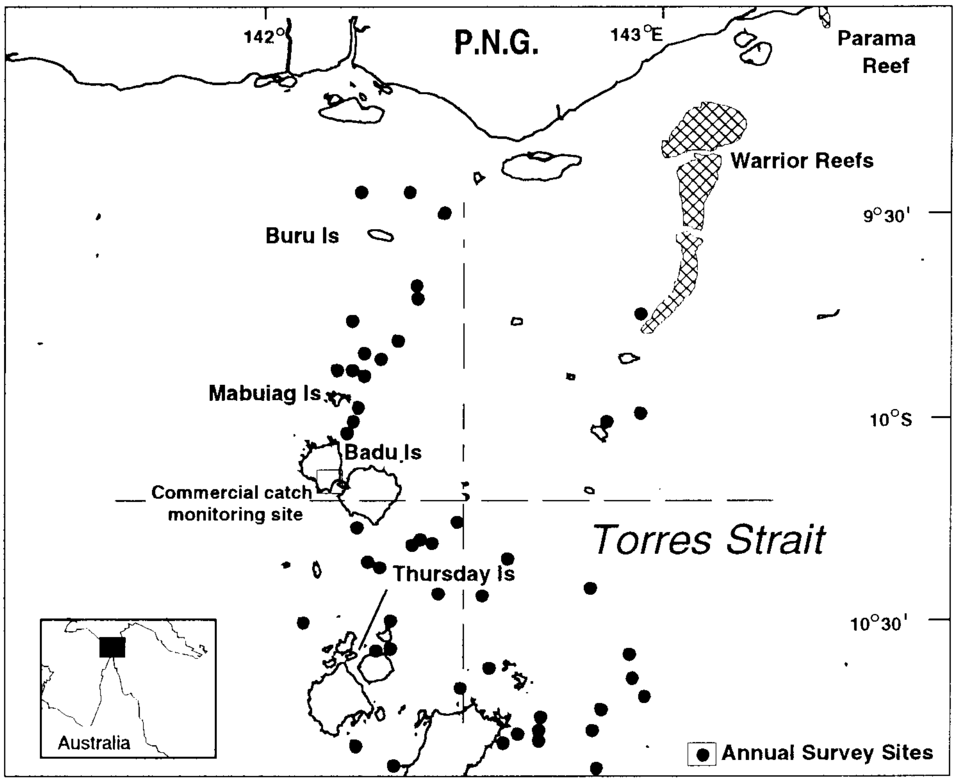


**Fig. 1.** Torres Strait, showing the sites surveyed annually between 1989 and 1996 (two dives were done 1–3 km apart at each site) and the arbitrary division of the study area into four quadrants to allow assessment of spatial differences in size of lobsters. P.N.G., Papua New Guinea.

Mix program (MacDonald and Pitcher 1979) to estimate the proportion and mean size of the recruiting 1+ and fished 2+ year-classes. These proportions were corrected with the 1+ and 2+ misses recorded by the divers during sampling. The corrected proportions provided a standardized index of the relative abundances of the 1+ and 2+ year-classes.

The total numbers of recruits ($N_{1+_y}$) and stock ($N_{2+_y}$) were estimated from the corrected proportions of the 1+ and 2+ year-classes (Table 1) relative to the benchmark stock estimate from the 1989 survey. This required rescaling the 1989 data to take into account the changed sampling methods by converting the 1989 'counts per (4 × 500 m) transect' to 'counts per (4 m × 20 min) swath' (given the transect times recorded in 1989) and converting the 1990 'counts per (20 min × visibility-limited width) swath' to 'counts per (20 min × 4 m) swath'. The visibility correction was 'swath width = 3 × (visibility × 0.75)' but with a maximum swath width of 12 m (given the visibilities recorded in 1990). The basis for this swath width was that divers were separated by about 0.75 × visibility and they scanned the area between them plus a similar area to the outside, but when visibility was 5 m or greater, divers swam about 4 m apart and each scanned about 4 m to the outside. Thus, the 571 lobsters counted on the subset of 100 (4 × 500 m) transects in 1989 were converted to 641 (per 100 (20 min × 4 m) swaths), and the 759 lobsters counted in 1990, during 20-min dives, were converted to 448 (per 100 (20 min × 4 m) swaths). By inference, if 20-min dives had been used in 1989 instead of 4 × 500 m transects, then approximately 1086 lobsters (i.e. 759 × 641/448) would have been counted in 1989.

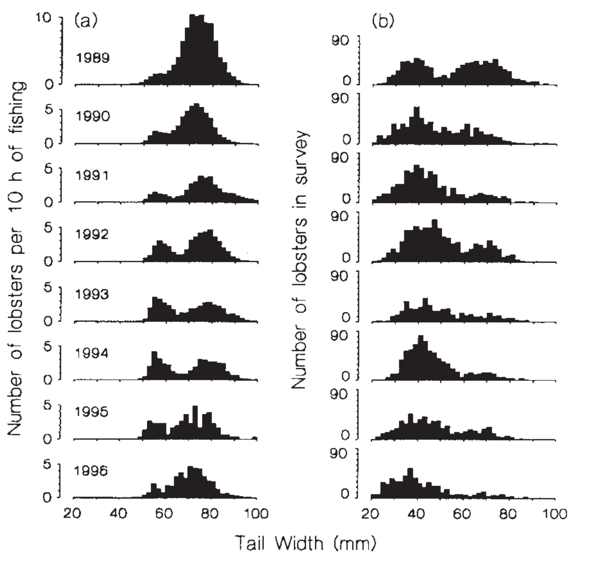


**Fig. 2.** Size–frequency distributions of (*a*) the lobster catch landed at Mabuiag and Badu Islands contrasted with (*b*) the size–frequency distributions of the Torres Strait lobster population surveyed by research divers in June from 1989 to 1996. Absolute size–frequencies for the survey and the catch (per unit effort) are presented to show interannual differences. The catch and survey are scaled differently.

Total mortality ($Z$) for the period of exploitation was estimated from the survey 2+ abundance ($N_{2+_y}$) each year ($y$ corresponded to June–June, not the calendar year) and 1+ recruit abundance in the previous year ($N_{1+_{y-1}}$):

$$Z_y = -\ln(N_{2+_y}/N_{1+_{y-1}}). \quad (1)$$

Fishing mortality ($F_y$) was estimated each year from the catch (tail weight in tonnes) of the fishery ($C_a$) per annum ($a$ corresponded to the calendar year, though the catch was almost entirely from the cohort corresponding to $Z_y$) and the mid-to-late-season survey legal-size biomass ($B_y$) by rearranging the equations for exploitation rate:

$$u = \frac{C}{B} \text{ and } u = \frac{F}{Z}\left(1 - e^{-Z}\right)$$

(Gulland 1983), giving

$$F_y \approx \frac{C_a}{B_y} \times \frac{Z_y}{\left(1 - e^{-Z_y}\right)} \quad (2)$$

(denoted hereinafter as $F_{expl.}$). Note that $B_y$ approximated $B_{average}$ for the season when $Z \approx 1$ (from cohort modelling; see next main section). Natural mortality ($M_y$) was estimated by

$$M_y = Z_y - F_{expl._y}. \quad (3)$$

Actual fishery yield per recruit ($YPR_y$) was estimated by

$$[YPR_y] = C_a/N_{1+_{y-1}}. \quad (4)$$

## *Results*

The size distributions of the catches and surveys differed greatly (Fig. 2). The Islander catch comprised almost entirely 2+ lobsters and was truncated at about 52 mm tail width at the lower end, corresponding to the minimum legal size of 100 mm tail length. The surveys showed large numbers of pre-recruit lobsters.

The 1989 survey showed a large 2+ cohort relative to the 1+ cohort, but in all subsequent years the 2+ cohort was smaller (Fig. 2). These trends in 2+ cohort abundance were also apparent in the catch data (Fig. 2, Table 1). Clearly, the 2+ year-class in 1989 was the largest seen during the period of the surveys; it also yielded the second largest catch ever recorded—only 1986 was larger (Table 1). Larger numbers of 1+ lobsters appeared in the catch when the average tail size of the 1+ cohort was larger and thus more tails were larger than the minimum legal size ($r$ = 0.892, $P$ = 0.003). The mean tail size of 1+ and 2+ cohorts varied considerably among years (Fig. 2, Table 1).

The Mix analysis provided proportions of the 1+ and 2+ year-classes each year (Table 1), which were used to compare the relative abundances of the 1+ and 2+ cohorts from the survey with those from the fishery, and among years (Fig. 3). Overall, the 2+ abundance indices from the survey and from the catch per unit effort (CPUE) correlated well ($r$ = 0.890, $P$ = 0.003); in particular, the relative changes from 1989 to 1990 are similar. However, for the remainder of the time-series (Fig. 3), the survey 2+ counts were more variable than was the fishery 2+ CPUE, particularly in 1992 and 1996. The survey 1+ counts were not correlated with the fishery 1+ CPUE ($r$ = 0.167, $P$ = 0.693); this was not unexpected, as only a small fraction of the 1+ cohort was caught by the fishery in June.

The estimated absolute cohort sizes in the main fishing grounds are also shown in Table 1. The 1+ recruiting cohort in 1996 was relatively small (about 5.99 million lobsters), and given the average total mortalities observed since 1990, the 2+ cohort in 1997 may be about 1.82 million lobsters, which is also relatively small. Hence, the 1997 catch may be among the lowest through the 1990s, depending on the level of fishing effort.

Estimates of total mortality ($Z_y$) and fishing mortality ($F_{\text{expl.}y}$) (Table 1) varied considerably among years and tended to increase. However, because the stock was not in a steady state, $F_{\text{expl.}}$ (Eqn 2) tended to overstate fishing mortality, especially when $Z_y > 1$. Natural mortality ($M_y$; Eqn 3) also varied considerably among years (0.42–1.14) and tended to increase. With the use of Eqn 2 for $F$, the average estimate of $M$ since 1990 was 0.687 (but see estimates from other methods below).

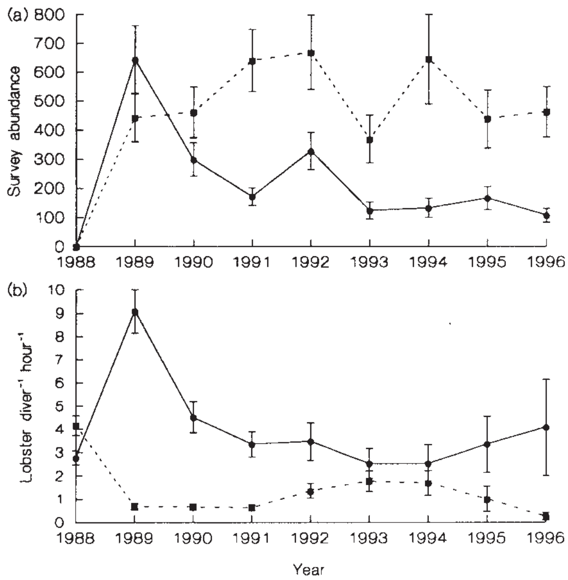


**Fig. 3.** *(a)* Numbers of (■) 1+ and (●) 2+ lobsters (±95% confidence intervals) counted during annual surveys of the Torres Strait lobster population between 1989 and 1996. *(b)* Catch per unit effort of (■) 1+ and (●) 2+ lobsters (±95% confidence intervals) caught by hookah divers at Badu and Mabuiag Islands between 1988 and 1996.

## Stock assessment modelling

The Gulland (1983) rule-of-thumb model in 1989 was inappropriate for the Torres Strait lobsters because recruitment was not constant and because, as a result of the breeding migration, $F$ was not constant after recruitment. To provide a more appropriate assessment, a cohort dynamics model was constructed that captured the main elements of the stock and fishery.

### *Methods*

The model initially was constructed when the first estimates of natural and fishing mortality rates became available after the first annual survey (in 1990). The model simulated a single unitary cohort, with monthly time steps starting at age 18 months (from hatching). The inputs included the following. The von Bertalanffy growth equation,

$$[CL] = L_\infty\{1 - \exp[-K(\tfrac{t}{12} - t_0)]\}, \qquad (5)$$

where C$L$ is carapace length, asymptotic carapace length $L_\infty$ = 177 mm, Brody coefficient $K$ = 0.386 year$^{-1}$, $t$ is age (months), and $t_0$ = 0.441 year, was estimated from tag–recapture data (Trendall *et al.* 1988). Relationships between carapace length and tail width (TW) and between tail width and tail weight (WT) were estimated from unpublished CSIRO data:

$$[\text{TW}] = \frac{[\text{CL}] - 1.089}{1.433} \quad \text{and} \quad [\text{WT}] = 0.001244[\text{TW}]^{2.955}. \qquad (6)$$

Fishing mortality ($F$, year$^{-1}$) and survival from fishing ($S_F$) were modified each month (thus $F_t$) by the recruitment selection curve ($p_t$, the proportion of $F$ applied to lobsters of age $t$ and size $L_c$), estimated by contrasting the catch and survey size-distributions (Fig. 2, Table 2), and by the seasonal relative effort patterns ($f_i$), estimated from freezer-vessel logbooks (AFMA data), where $i$ is month of the year, i.e. $i = (t + 6) \bmod 12$:

$$F_t = p_t f_i \frac{F}{12} \quad \text{and} \quad S_F = e^{-F_t}. \qquad (7)$$

The model total yield ($Y_{\text{total}}$) was accumulated from yield by month ($Y_t$):

$$Y^t = N_t \frac{F_t}{\left(F_t + \frac{M}{12}\right)}\left(1 - S_\text{M} \times S_\text{F}\right)[\text{WT}] \quad \text{and} \quad Y_{\text{total}} = \sum_{t=18}^{48} Y_t, \qquad (8)$$

where $M$ is natural mortality rate (year$^{-1}$) and $S_\text{M} = e^{-M/12}$ is monthly survival from natural mortality.

A cohort decay function calculated, each month ($t$), the decline in the number of lobsters ($N$) in the cohort:

$$N_{t+1} = N_t S_\text{M} S_\text{F} X_t, \qquad (9)$$

where $X_t$ is a seasonal emigration parameter (Table 2) estimated from monthly catch per effort and from size distributions (Skewes *et al.* 1994). The model months were incremented until 48, although almost all lobsters were emigrated at age 32–33 months. The entire fishery was treated as a uniform whole; it was not spatially partitioned except for the exit of emigrated lobsters, which were not exploited. There was no analogy of the severe mortality at Yule Island (Dennis *et al.* 1992), and no stock–recruitment relationship was included.

A range of values of $M$ (e.g. 0.5–1.1) and $F$ (i.e. 0.0–2.0 in steps of 0.05) was used in the model. A range of minimum sizes ($l_s$ = 75–130 mm tail length) was examined by shifting the months (and thus size) when the recruitment curve ($p_t$) was applied, though for status assessment $l_s$ = 100 mm tail length, the current minimum legal size.

Outputs from the model were cohort numbers and yield by month, cohort total yield, and numbers remaining at the beginning of the emigration, for the specified ranges of $M$, $F$ and $l_s$. These allowed estimation of the following indicators of stock status.

The proportion of the population that escaped fishing to emigrate and breed was estimated as the number surviving at the end of month $t$ = 31, as a proportion of the maximum survivors when $F$ = 0.0. In the absence of a known stock–recruitment relationship, a level of escapement of about 70% was chosen as a conservative reference level.

**Table 2. Key parameters underlying the stock assessment model for the ornate rock lobster: *(a)* size-selection (length-at-capture) curve (proportion of $F$ by size, $p_t$) for $l_s$ = 100 mm tail length; *(b)* seasonal emigration coefficients ($X_i$); and *(c)* seasonal relative effort ($f_i$)**

*(a)*

| Month | Age (months) | Size (mm tail length) | $p_t$ |
|---|---|---|---|
| ≤July | ≈19 | ≈84 | 0 |
| August | 20 | 89 | 1 |
| September | 21 | 94 | 3 |
| October | 22 | 98 | 10 |
| November | 23 | 103 | 33 |
| December | 24 | 107 | 66 |
| January | 25 | 111 | 90 |
| February | 26 | 115 | 97 |
| March | 27 | 119 | 99 |
| ≤April | ≤28 | ≤126 | 100 |

*(b)*

| Month | Age (months) | Size (mm tail length) | $X_i$ |
|---|---|---|---|
| August | 32 | 136 | 0.525 |
| September | 33 | 139 | 0.095 |
| August | 44 | 168 | 0.525 |
| September | 45 | 171 | 0.095 |

*(c)*

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $f_i$ | 0.6 | 0.6 | 0.8 | 1.0 | 1.3 | 1.5 | 1.5 | 1.5 | 1.5 | 1.1 | 0.2 | 0.4 |

Yield per recruit ($YPR_{model}$) was estimated simply as the total yield from the model unitary cohort (Eqn 8) for the ranges of $M$, $F$ and $l_s$. The potential yield in the following year ($C_{y+1}$) was estimated by multiplying the model YPR (at $F$ = 0.4) by the recruit ($N_{1+_y}$) abundance; natural mortality was set at the average since 1990 (i.e. $M \approx 0.8$) because annual differences could not be known in advance.

Fishing mortality was estimated by 'inverse' YPR ($F_{YPR}$). This involved estimating actual $YPR_y$ from Eqn 4 and finding the same value of $YPR_{model}$ in the model output and noting the corresponding model $F$. In this case, model $M$ was chosen as the average estimate for the period of the surveys (i.e. approximately 0.8).

Fishing mortality was also estimated by comparing estimates of actual $YPR_y$ and $Z_y$ (Eqns 1 and 4) from catch and survey data with the simulated $YPR_{model}$ at a range of model $M$ and $F$. Both YPR and $Z$ are functions of $M$ and $F$ that could be handled as a pair of simultaneous equations:

$$[YPR] = h(F, M) \text{ and } Z = F + M. \qquad (10)$$

This was done graphically by representing the model results as a surface of iso-lines for $M$ and $F$, with respect to model YPR and $Z$. The estimates of actual $YPR_y$ and $Z_y$ were plotted onto the model surface and the corresponding $M$ and $F$ were estimated from the iso-lines, for each year. Estimates of fishing mortality from this method ($F_{YPR/Z}$) were not biased by the assumptions of a steady state or prior values of $M$ inherent in the methods described above.

## *Results*

In 1989, an estimated 7 million lobsters emigrated from Torres Strait to breed, and given a catch of 243 t and a corresponding model estimate of $F \approx 0.13$, this was about 90% of the numbers that could have emigrated if there was no fishing at all. If fishing mortality had been $F$ = 0.4 in 1989, the escapement would have been about 73% (Fig. 4) and the estimated yield over 800 t.

In subsequent years, advice on potential yield was also provided at the reference level of $F$ = 0.4. The potential yield varied from year to year (Table 1) because of recruitment fluctuations. For example, in 1993, with $YPR_{model} \approx 42$ g at $F$ = 0.4 and $M$ = 0.8 and with about 8.68 million 1+ recruits in the previous year, the potential yield was 365 t (8.68 × 42); in 1994, the potential yield was 200 t (4.78 × 42). With 5.99 million 1+ recruits estimated in 1996, the yield advice at $F$ = 0.4 for 1997 was 250 t (Table 1).

The analysis of yield per recruit (Fig. 5) showed that for $F \approx 0.4$ and $l_s$ = 100 mm tail length, $YPR_{model}$ was about 56–32 g, depending on natural mortality in the range $M$ = 0.5–1.1. At the current values of $F$ (0.2–0.5), the shape of the iso-yield lines (Fig. 5) indicated that yield would have been slightly greater at smaller minimum sizes, although at F >> 1.0 the highest $Y_{PR}$ occurred at about $l_s$ = 100 mm tail length.

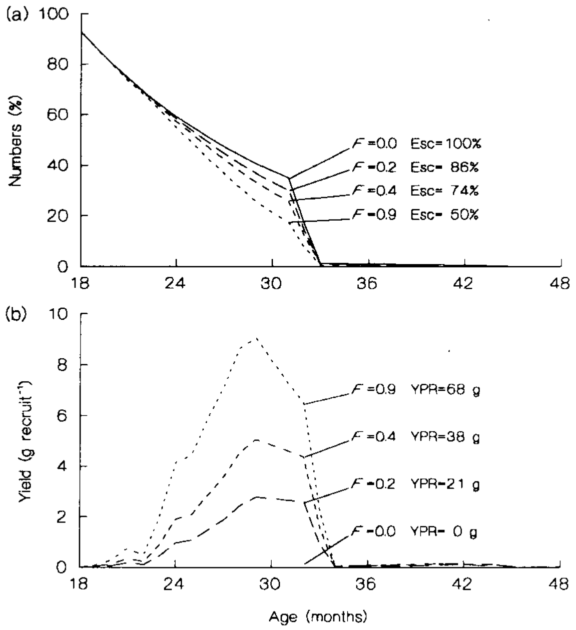


**Fig. 4.** Proportional changes in *(a)* model abundance and percentage escapement and *(b)* monthly and total yield per recruit (YPR) for a unitary cohort of ornate rock lobsters following recruitment at age 18 months, for four levels of fishing mortality (*F*), with *M* = 0.9. Emigration occurred during months 32–33 and 44–45.

Fishing mortality estimated by 'inverse' $Y_{PR}$ ($F_{YPR}$; Table 1) varied considerably among years and tended to increase, as observed for $F_{expl.}$ above. Natural mortality (from Eqn 3, but substituting $F_{YPR_y}$) also varied considerably among years (0.51–1.5) and tended to increase; the average estimate since 1990 was *M* = 0.91.

Fishing mortality estimated by graphical analysis (Fig. 6) of simultaneous functions for $Y_{PR}$ and *Z* (Eqn 10) was less variable than that calculated with previous methods, though it still tended to increase ($F_{YPR/Z}$; Table 1). The estimates of *M* (from Eqn 3, but substituting $F_{YPR/Zy}$) were variable (0.55–1.36; Fig. 6) and showed a weak ($r^2$ = 0.12), non-significant (*P* = 0.5) trend of increasing with time. With this method, the average *M* since 1990 was 0.895.

## Discussion

The fishery-independent estimates of the relative abundances of the two cohorts of lobsters in Torres Strait, from annual diver surveys, provided the basis for stock assessment, which was simplified by two clearly separated cohorts, each fished sequentially for about one year.

The stock assessments used a conservative reference level for escapement of >70%, which corresponded to $F \approx 0.4$ in estimating potential yields. This conservative target was chosen because of the uncertainties in the assessment, the simplicity of the model, the unknown

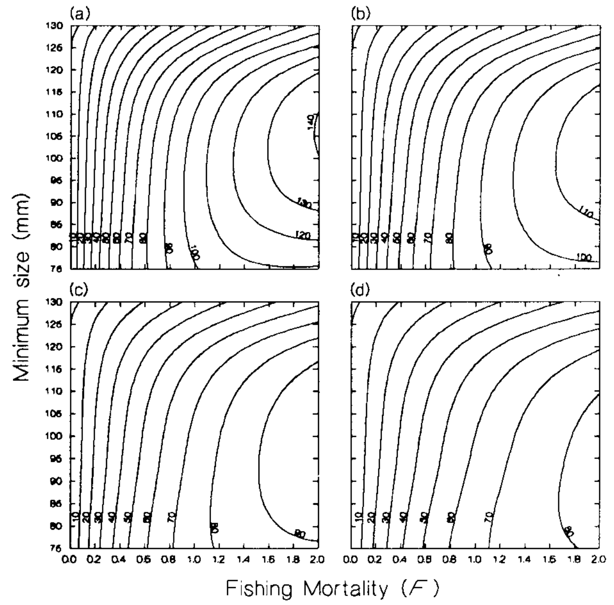


**Fig. 5.** Yield-per-recruit surfaces for a range of minimum sizes (mm tail length) and values of fishing mortality (*F*), with natural mortality set at *(a)* *M* = 0.5, *(b)* *M* = 0.7, *(c)* *M* = 0.9 and *(d)* *M* = 1.1. Contours show lines of constant yield per recruit (grams).

extent of the breeding grounds, and the evidence indicating that these lobsters breed only once and then die (Dennis *et al.* 1992)—a situation unlike that in any other lobster

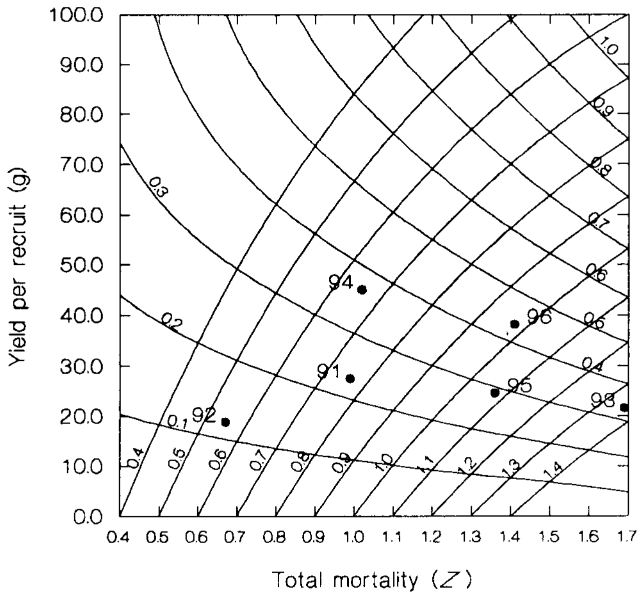


**Fig. 6.** Plot of (●) yield per recruit versus total mortality for the fishery for the years 1991–96, with underlying simultaneous model surfaces (based on [YPR] = *h*(*F*, *M*) and *Z* = *F* + *M*) for fishing mortality (*F* = 0.1–1.0) and natural mortality (*M* = 0.4–1.4). Contours show lines of constant *F* (upper left to lower right) and constant *M* (lower left to upper right).

fishery. Finally, there was no information available on stock–recruitment relationships that might have assisted in estimating sustainable escapement rates.

*Indicators of current stock status*

The abundance of 1+ recruits varied considerably among years, but there was no clear downward trend in recruitment (Fig. 3). The observed low recruitments (e.g. in 1993; Figs 2 and 3) were probably a result of natural fluctuations.

Analysis of yield per recruit showed that the stock was not growth-overfished at current values of $F$ (0.2–0.5). In fact, slightly higher $Y_{PR}$ might have been obtained at minimum sizes smaller than the current tail length of 100 mm (Fig. 5). However, at very high $F$, the current minimum size would eventually become appropriate.

Annual catches for the 1990s have varied around 200 t, and though they are lower than the peak catches of 349 t in 1986 and 243 t in 1989, they are generally higher than the catches before 1986 (Table 1) and have been close to the long-run average. To maintain these catches, however, fishing effort and fishing mortality appear to have increased over the past 5–10 years (Fig. 7).

The upward trends in estimated effort have taken estimated fishing mortality into the vicinity of or past the initial target of $F = 0.4$. Also, in 1994, the actual catch (216 t) exceeded the yield advice (200 t) at $F = 0.4$. Nevertheless, these assessments were conservative and the indications were that the fishery was sustainable. With the current $F$ values of 0.3–0.5 (Fig. 7), recruitment-overfishing was unlikely.

*Environmental effects on the stock*

Environmental variation adds uncertainty to any stock assessment, particularly variability in recruitment processes. In Torres Strait, local environmental changes (i.e. a seagrass dieback and subsequent sediment movement in north-western Torres Strait during 1991–93) modified the availability of suitable settlement and nursery habitat. This dieback may have affected settlement success, post-settlement survival and movement patterns.

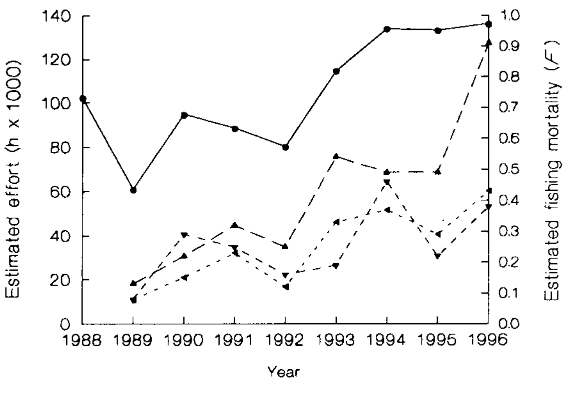


**Fig. 7.** (●) Estimated effort (from catch or catch per unit effort), and estimated fishing mortality ($F$) from three methods (see text): (▲) exploitation and $Z$, (▼) 'inverse' YPR, and (◀) simultaneous model surfaces for [YPR] = $h(F, M)$ and $Z = F + M$.

*Uncertainties in the assessment process*

The model included a single constant growth function, but growth rates differ spatially and temporally (Skewes *et al.* 1997). Further, the model did not take into account variance in size-at-age and size–weight relationships; these relationships are likely to have a significant influence on stock assessment because they are non-linear.

There were also uncertainties in estimating $F$. Different methods gave different results (Table 1) because there were small numbers of 1+ recruits in the catch and annual catches were recorded over calendar years, which did not match the timing of recruitment into and emigration from the fishery. Eqn 2 overestimated $F$ because the stock was not in a steady state and 2+ biomass would have been reduced by mortality.

Estimates of natural mortality also varied, but a constant $M$ (i.e. an average of ~0.8) was used in providing advice on future yield because annual differences could not be known in advance, and this introduced error. Some of the variability in $M$ may have been caused by environmental factors such as the seagrass dieback.

Other uncertainties included: variability in the timing of settlement, sampling errors in the survey data, the distribution of fixed survey sites relative to lobster movements, variability in seasonal effort patterns, variability in the size-selection curve, and the catch of the PNG fishery.

*Implications for management*

The yield-per-recruit analysis confirmed that lobsters were not being harvested at too small a size. Consequently, enforcement of the minimum size limit (which has a substantial cost) could be reviewed—it may have been sufficient for processors to limit capture sizes by not purchasing very small tails that have lower value. In addition, the closed season for hookah equipment in October–November would be unlikely to have the reputed benefits of increasing subsequent yield or substantially increasing escapement.

The first assessments of the Torres Strait lobster stock showed that exploitation was low, and it was recommended that increased involvement by Islander divers could be encouraged. However, the lower recruitments and increased fishing mortality since then mean that new management measures may, in future, need to be considered to address the uncapped effort potential in the fishery. Assessments still indicate that, on average, there is potential for increased catches for this fishery—the projected long-term potential annual yield is about 275 t at $F = 0.4$, based on the average recruitment since 1989. Also, it is possible that higher $F$ could be sustainable, perhaps $F \approx M \approx 0.9$, with an escapement of approximately 50%. The actual yield will vary from year to year because of fluctuations in recruitment and effort.

The uncertainties in the assessments were not a major concern in the past, when $F$ estimates were less than 0.4, because the likelihood that the stock was overfished was low. But, with the recent upward trends in fishing effort and mortality, the risks associated with errors in the assessment due to the uncertainties are higher. Consequently, it has become a priority to address the uncertainties and further develop the model.

### *Priorities for future development*

To address several uncertainties, the model will be developed further. Sensitivity analyses will guide priorities placed on refining each aspect of the model. New information about growth will be incorporated: e.g. variance in size-at-age and size–weight relationships, spatial and seasonal differences, and density-dependent effects.

The catch of the 1+ and 2+ cohorts will be separated and total annual catches will be summed over the period September–August to match the timing of recruitment and emigration. Seasonal effort patterns and size-selection (recruitment) curves will be updated. AFMA and NFA catch and effort logbook data will be incorporated.

Several other uncertainties will be difficult to incorporate because information on their characteristics is difficult to obtain or predict. Nevertheless, by addressing the tractable uncertainties, further development of the assessment model will assist in setting new fishery target indices and approaching them with confidence.

## Acknowledgments

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# Constructing abundance indices from scientific surveys of different designs for the Torres Strait ornate rock lobster (*Panulirus ornatus*) fishery, Australia

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**Abstract**

Fishery-independent surveys of the ornate rock lobster (*Panulirus ornatus*) population in Torres Strait were carried out annually from 1989 to 2002 with variation in design and implementation due to logistic and funding constraints. Fixed and random station surveys were modeled separately, and their results were contrasted. As all the survey data contain many zero records, a gamma-based generalized linear model was used for non-zero records and a Bernoulli based model for the probability of encountering a lobster. Abundance indices for fished and recruiting year-classes were then constructed by combining the results from both models. To select an appropriate error model, four alternatives-log-normal, log-gamma, Poisson, and negative binomial-were explored. The results show that a log-gamma model best estimated the non-zero encounter rates. Recruiting (age 1+) lobsters exhibit a more variable distribution in space; however, for fished (age 2+) lobsters there is greater temporal variation in the probability of encountering lobsters. The large-scale pattern of lobster distribution among sampling strata remained unchanged over the survey period. In contrast to the results from the annual fixed station surveys (1989–2002), the models for the stratified random surveys (1989 and 2002) showed that the small-scale patterns in lobster distribution over depth did change between years. This may undermine the suitability of fixed station surveys for the construction of relative abundance indices of the Torres Strait lobster population.


*Keywords:* Lobster; *Panulirus ornatus*; Abundance index; Generalized linear model

## 1. Introduction

The ornate rock lobster (*Panulirus ornatus*) has been fished by the traditional inhabitants of Torres Strait, between Australia and Papua New Guinea, probably for several centuries. A commercial fishery developed in the late 1960s, following the establishment of a seafood processing factory on Thursday Island. Involvement of islanders in the fishery increased during the 1980s, and the lobster fishery has now become a major source of income for Torres Strait islanders (Pitcher et al., 1997). The annual landings of lobster tails was about 300 t on

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average over the last decade, 75% from the Australian fishery and 25% from the Papua New Guinean fishery (Pitcher et al., 2002).

Lobster fishing in Torres Strait is carried out exclusively by divers working from 4 to 6 m tenders as this species will not readily enter baited traps (Pitcher et al., 1992). The divers use a short hand spear or snare either with surface supplied air (hookah) or free diving. Divers fish down to about 25 m in depth and dive only during daylight hours. The fishery is managed under the Torres Strait Fisheries Act 1984 agreed to by Australia and Papua New Guinea "to maintain the sustainability of the fishery, to encourage islander participation in the fishery and to promote economic development in the Torres Strait area without any adverse impact on the traditional way of life and livelihood of the traditional inhabitants".

With the increasing pressure to address the long-term sustainability of the fishery through effective management, lobster research shifted focus from fisheries ecology and biology to stock assessment in the late 1980s. Fisheries assessment, however, relies greatly on data sufficiency. While catch statistics have been collected at the point of processing since the late 1970s, fishing effort data from the freezer boat sector of the commercial fishery has only been available since 1994, through a voluntary logbook system. This system is now compulsory for all freezer boats. Without fishing effort information, a stock abundance index becomes essential for most forms of stock assessment. As lobster abundance could not be estimated from logbook data, CSIRO initiated an annual fishery-independent survey of the lobster population in Torres Strait in1989 (Pitcher et al., 1992). The annual surveys was carried out in all subsequent years, but its design and implementation have not always been consistent. This paper presents approaches to constructing standardized abundance indices for the Torres Strait lobster fishery based on scientific surveys of varying types and discusses the potential consequences of the different survey designs.

## 2. Materials and methods

### 2.1. Field survey

A pilot survey was conducted in 1988 to assess the feasibility of estimating the standing stock of lobsters in Torres Strait and to determine the most effective sampling strategy (Pitcher et al., 1992). Based on the results of the pilot survey, a full-scale survey was then designed and carried out during 7 weeks in May–June 1989. The survey covered about 25,000 km$^2$ in Torres Strait between Australia and Papua New Guinea (Fig. 1). The entire survey area was divided into 2650 sites (each being a $3 \times 3$ km block), which were stratified based on habitat, and a total of 271 sites were randomly selected with the number in each stratum proportional to its known area. Two transects were randomly selected within each site (Table 1; for details see Pitcher et al., 1992).

Transects were located with a combination of satellite fixes and radar position fixes from the supporting vessel, or multiple compass bearings to mapped features. Paired divers swam side by side along a 500 m transect line laid on the seabed and used a 2 m rod to measure the transect width. They recorded lobsters within 2 m of the transect line on each side. Hence, a

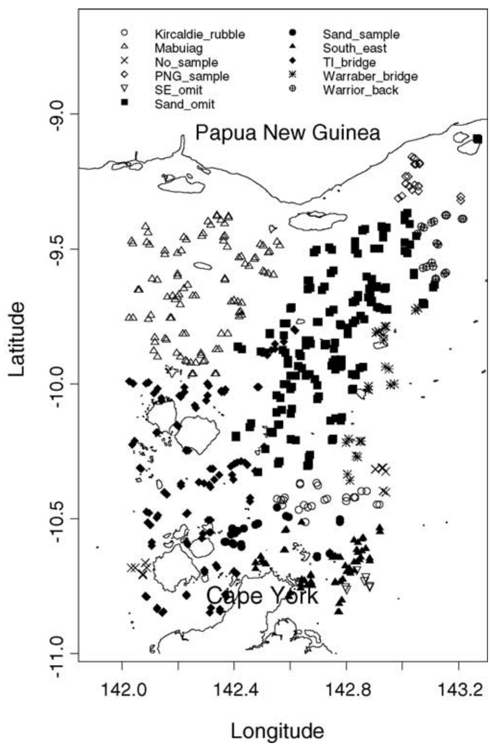


Fig. 1. Sampling sites and stratification of the lobster field survey in 1989.

Table 1
Specification of the survey implementation (sample design and transect methods) from 1989 to 2002

| Year | No. of transects/sites | GPS distance | Chainman distance | Time swum | Spearing |
|---|---|---|---|---|---|
| 1989 | 542(271) | No | Fixed at 500 m | Measured | No |
| 1990 | 100(50) | No | Not used | Fixed at 20 min | Yes |
| 1991 | 100(50) | No | Not used | Fixed at 20 min | Yes |
| 1992 | 100(50) | Yes | Not used | Fixed at 20 min | Yes |
| 1993 | 100(50) | Yes | Not used | Fixed at 20 min | Yes |
| 1994 | 100(50) | Yes | Not used | Fixed at 20 min | Yes |
| 1995 | 100(50) | Yes | Not used | Fixed at 20 min | Yes |
| 1996 | 82(41) | Yes | Partially used | Fixed at 20 min | Yes |
| 1997 | 82(41) | Yes | Not used | Fixed at 20 min | Yes |
| 1998 | 82(41) | Yes | Fixed at 500 m | Measured | Yes |
| 1999 | 82(41) | Yes | Fixed at 500 m | Measured | Yes |
| 2000 | 82(41) | Yes | Fixed at 500 m | Measured | Yes |
| 2001 | 82(41) | Yes | Fixed at 500 m | Measured | Yes |
| 2002 | 354(313) | Yes | Fixed at 500 m | Measured | Yes |

belt transect 500 m × 4 m was covered by the divers at a single transect.

Overall, zero lobsters were recorded at 72% of the survey transects in 1989. It is not efficient to spend the majority of sampling effort surveying areas with zero or very few lobsters as the distribution of lobsters is related to habitat (Pitcher et al., 1992) and does not significantly change from year to year. Hence, after omitting the strata with very low lobster abundance, a sub-set of 50 sites (100 transects) that had the highest densities of lobsters in the area was selected for abbreviated fixed station surveys in the subsequent years (Fig. 2). This sub-set accounted for 86% of lobsters observed in the 1989 survey. The survey was further downscaled to 41 sites (82 transects, Fig. 2) in 1996 due to funding constraints. After a decade of monitoring the lobster population with fishery-independent surveys there was concern that if the distribution of lobsters had changed since 1989 the sub-set of sampling sites may no longer be representative. To address this concern, another full-scale survey of 313 sites (354 transects) was conducted in 2002 (Table 1), consisting of the 41 repeated sites, which were sampled in all the previous surveys, and new randomly selected sites (Fig. 3). To increase its efficiency, some strata of very low or zero lobster density were excluded. The 41 repeated sites had two transects at each site to keep consistency for monitoring purposes, but the newly selected sites had only one transect at each site to increase the spread of sites in the study area (Fig. 3). The sample sites were allocated to each stratum based on the proportion of

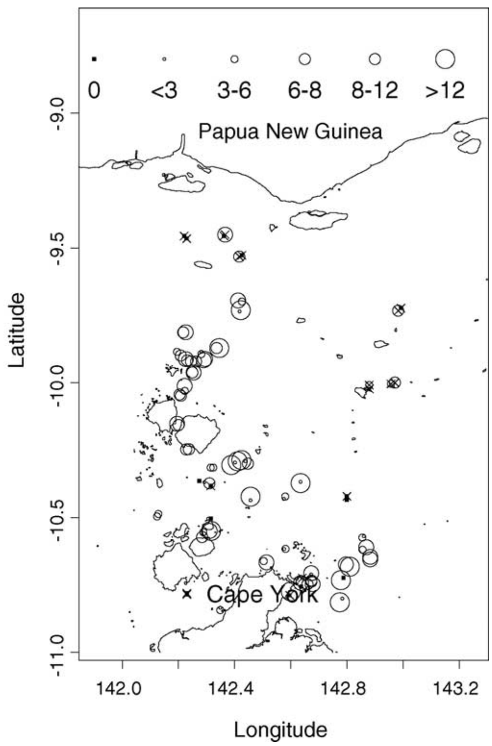


Fig. 2. The fixed sampling sites (50/41) surveyed annually between 1990 and 2001. The crosses indicate the sites not sampled between 1996 and 2001. The size of the circles is proportional to the 1991 encounter rates (lobsters per 4 m× 500 m transect).

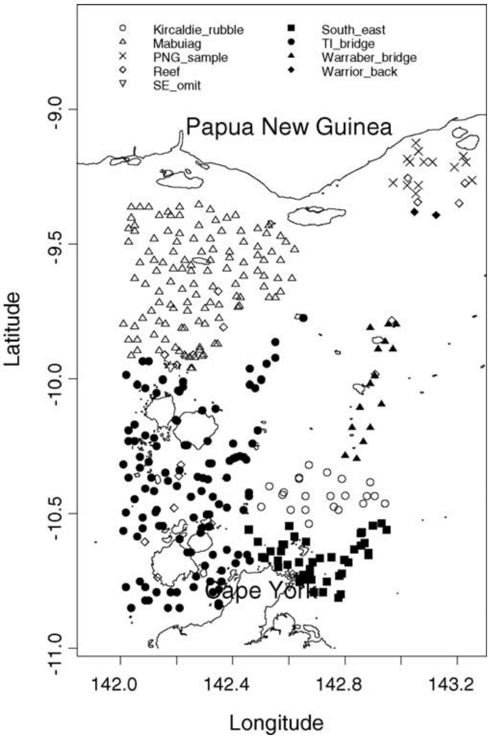


Fig. 3. The sampling sites and stratification of the field lobster survey in 2002.

the product of area size and variance. To minimize the effect of possible migration/movement, the survey was carried out at a similar time (May/June) each year.

Besides the change in the number of survey sites, implementation of the annual surveys also changed from time to time (Table 1). The strict control over transect length in 1989 was replaced with a time control of 20 min from 1990 to 1997 to reduce the time spent at each site in laying a transect line. The 20 min duration was chosen based on the average time required to swim 500 m in 1989. However, this change caused great variation in the actual lengths of the transects because the distance a diver can swim in a certain period of time can vary greatly, depending on the speed of current and the number of lobsters the diver encounters. In contrast to the 1989 survey which employed a professional fisher to sample lobster sizes, in all remaining years lobsters were speared by the research divers during the transect surveys to provide age composition information. Portable GPS was also used to measure the length of transects from 1992 to 2002.

The full-scale survey in 1989 was designed to provide an absolute abundance estimate for the lobster population based on the swept area method. The subsequent annual surveys from 1990 to 2001 served as a monitoring program and were supposed to provide abundance indices relative to the 1989 estimate. The 2002 full-scale survey also provided an updated estimate of absolute abundance but also provided an opportunity for comparison between the abundance estimate calculated from the 1989 survey and the relative indices derived from the 50/41 fixed sites from 1989 to 2002 and that directly calculated from the 2002 survey through the use of the swept area method. Two types of abundance indices can be constructed from the survey data: one based on the 50/41 fixed sites from 1989 to 2002, and the other using data from all the survey sites just in 1989 and 2002. Only 41 of the 313 sites surveyed in 2002 are repeat sites from the 1989 survey, and the stratifications are very similar except that the sandy areas, unsuitable as lobster habitat, were omitted in 2002 (Figs. 1 and 3). Therefore, these two years' surveys can be treated as independent stratified-random surveys. A comparison of the abundance estimates between the fixed and random station surveys is not only of scientific interest, but also provides insights into the construction of stock abundance indices for the lobster fishery.

During the annual surveys the lobster population in Torres Strait is comprised of two major age groups, 1+ and 2+ year old (where + denotes the variable larval duration of approximately 6 months) (Pitcher et al., 1992). The age composition information from the distribution of speared lobsters was used to split these two age groups at each site. Although the survey data were originally recorded by transect, the statistical analyses in this study were carried out based on site information, i.e. the counts of lobsters in the two transects at one site were first averaged, because sites were treated as the primary sampling units.

### *2.2. Data imputation and standardization*

Lobsters are benthic animals and their density is well described by the number of lobsters per unit area. We define the unit area as $4\,\mathrm{m} \times 500\,\mathrm{m}$ in this study because (1) transect length was 500 m (measured with a transect line or a Chainman™ device) and its width was 4 m (measured with a rod) in almost half of the survey years; (2) the transect line and chainman-measured distances are the most reliable. The variation in survey method (Table 1) has meant that the calculation of lobsters per 4 m × 500 m transect was not always possible. We, therefore, developed functional regression models to impute the missing values. Other factors that affect the counting of lobsters such as spearing are also modeled and their impact is accounted for in the measurement standardization.

### 2.3. Generalized linear model

Abundance indices can be constructed with various approaches: linear methods, stratified analysis (Cochran, 1977), kriging (Petigas, 1993), or semi-parametric regressions such as generalized linear models (McCullagh and Nelder, 1989), and generalized additive models (Hastie and Tibshrani, 1990). This study uses a generalized linear model (GLM) because (1) a large proportion of the survey site counts are zeros; (2) the survey design is not balanced; (3) in GLM the distribution of the response variable is not limited to normal, but any of the exponential family and the relationship between the response and the explanatory variables need not be simple (identity).

The information available for each site is: encounter rate (number of lobsters per standard transect); year; stratum; depth; swimming time; whether GPS and chainman are used for distance measurement. The GLM is as follows:

$$g(R_{ysdt}) = \mu + \alpha_y + \alpha_{yt} : \log(t) + \alpha_s + \alpha_d + \cdots + \varepsilon_{ysdt} \qquad (1)$$

where $R_{ysdt}$ is the encounter rate in year $y$, stratum $s$, swimming time $t$, and depth $d$; $\mu$ the overall mean at the reference levels of all variables; $\alpha_i$ the effect of factor $i$ at a certain level relative to its reference level to allow for arbitrary abundance fluctuations between factor levels; $\varepsilon_{ysdt}$ the error term accounting for all other differences between encounter rates, and $\cdots$ is other factors or interaction terms that influence lobster encounter rate. $g(\cdot)$ is a link function, depending on the error model used. Swimming time, $t$, enters as a log-linear term, and $\alpha_{yt} : \log(t)$ indicates that separate linear regression models on $\log(t)$ are fitted within the levels of the year factor (Venables and Ripley, 2002). So, coefficient, $\alpha_{yt}$, has a different value for each year and reflects the marginal increase in encounter rate for each minute spent on swimming.

It is necessary to specify the distribution of the errors in the dependent variable in Eq. (1) in order to fit it to the data. Several error models can be employed: log-normal, log-gamma, Poisson, and negative binomial. The first two models are not compatible with zeros, and some adjustment is required for records of zero values. A common practice is to add a small constant either to all records or only to the zeros or completely ignore all records in which encounter rate is zero. The results, however, may be highly sensitive to the value added (Punt et al., 2000), particularly when a large percentage of the data records are zeros, such as in this case. Poisson and negative binomial models allow zero values to be included in the analyses, but the dependent variable in this case is the nearest integer to the encounter rate.

Another way to deal with zeros in the data is to account for both the probability of encountering lobsters and the number of lobsters encountered given that the count is not zero by classifying explicitly this dichotomy of the data into two categories, zero values and non-zero values (Ye et al., 2001). The non-zero encounter rates can be modeled using Eq. (1) with log-normal, log-gamma, Poisson, and negative binomial error models, while whether the encounter rate is zero or non-zero can be modeled as a Bernoulli random variable, i.e. binomial error model is assumed when fitting to the data (Stefansson, 1996; Punt et al., 2000; Ye et al., 2001).

To model the probability of non-zero encounter rates, the data were first recorded so that, for each transect, the value 0 was assigned if no lobster was found, and the value 1 was recorded if lobsters were counted to obtain Bernoulli type 0/1-measurements. The model for probabilities is via the logit function with binomial distribution, so that if the probability of a non-zero value is thought to depend on some variables, then it would be appropriate to model the existence of a non-zero count in a site as a Bernoulli random variable with probability, $P$, given by

$$\eta(P_{ysdt}) = \mu' + \alpha'_y + \alpha'_{yt} : \log(t) + \alpha'_s + \alpha'_d + \cdots + \varepsilon'_{ysdt} \qquad (2)$$

where $\eta$ is the logit link function, and the parameters have the same meanings as in Eq. (1). After the two distinct components, the probability of a non-zero count and the value of the encounter rate, given that some lobsters are found, are modeled separately, the unconditional encounter rate is then given by their product.

A GLM is more often used to extract the effect of a specific factor in fisheries such as year and month (e.g. Kimura, 1981; Stefansson, 1996; Kimura and Zenger, 1997; Punt et al., 2000; Ye et al., 2001). In contrast, this study concentrates on temporal variation in stock abundance. Effects of factors that have no interactions are quite clear from the coefficients, but high-order terms should be combined with their lower-order relatives. For example, an interaction between two factors should be combined with the main effects marginal to the interaction.

To best model the lobster survey data, we apply both methods. One treats zeros and non-zeros separately and the other does not, and then with each method we compare four error models, i.e. log-normal, log-gamma, Poisson and negative binomial. Akaike Information Criterion (AIC; Akaike, 1974) is used in variable selection for all GLMs. We start with a main-effect model including all variables and remove and/or add terms up to two-way interactions according to its impact on AIC value.

## 3. Results and discussion

### 3.1. Imputation and standardization

A significant multiple linear relationship was found between GPS distance ($L_g$, m), as the dependent variable and time spent on swimming a transect ($t$, min), number of lobsters speared in a transect ($N$), water depth ($D$, m) and current speed ($C$, knots) as explanatory variables

$$L_g = 22.3(0.99)t - 5.3(1.16)N + 4.2(1.00)D + 251.4(10.81)C \quad (3)$$

where figures in brackets are standard errors. This model was forced through the origin to meet the logic that when all the predictors assume a value of zero, the distance should also be zero. The functional regression is highly significant and explained 93% of the variability in data.

A diver swims 22.3 m per min on average (Eq. (3)). Spearing a lobster costs the diver 5.3 m or 14.3 s of time. The time spent on counting lobsters should be negligible and is not considered here. We assumed that divers made random decisions about whether they speared a lobster or not. So, the more lobsters divers encountered, the more they speared, and consequently the shorter distance they swam in a given period of time. Or, put another way, the more time a diver takes for a given distance, the higher the lobster density. Both water depth and current speed have a positive impact on GPS distance. This is because the GPS measures distance between the point a diver leaves the boat and the point a diver surfaces at the end of the transect. The time a diver takes to swim to the bottom at the beginning and to swim to the surface at the end increases with the depth of water. The increased time means a diver will drift further away in the current, and the difference between the transect length on the sea bottom and the distance on surface is certainly proportional to the speed of current.

A regression model of chainman measured distance against GPS measured distance was developed to impute transect length for those that did not have chainman-distances, but only recorded GPS distances

$$L_c = 181.7(14.7) + 0.53(0.03)L_g \quad (4)$$

where $L_c$ is the transect length (m) measured with chainman; $L_g$ the length (m) measured with GPS; the figures in brackets are standard errors. Eq. (4) was not forced through the origin because (1) there is a difference between the transect length at the bottom and the distance on the sea surface as discussed above, and (2) for imputation purposes reliability of model prediction is more important. This model explained 71% of the data variation (Fig. 4). Substituting Eq. (3) into Eq. (4), we have

$$L_c = 181.7 + 11.8t - 2.8N + 2.2D + 133.2C \quad (5)$$

In 1989, divers did not spear any lobsters, and Eq. (5), after setting $N$ to zero, was used to adjust the length for the transects where lobsters were found.

The above procedure standardizes all the survey encounter rates to lobsters per 4 m × 500 m transect. Fig. 2 shows the spatial distribution and relative levels

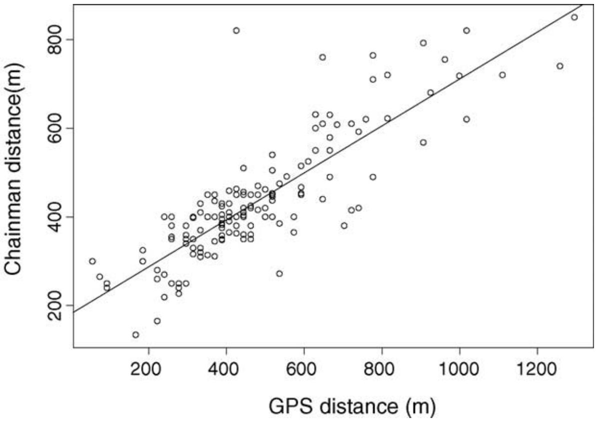


Fig. 4. Relationship between chainman measured distance and GPS measured distance.

of the 1991 encounter rates. It is readily apparent that the lobster population has a very patchy distribution in Torres Strait.

### 3.2. Model selection

We first applied Eq. (1) to the entire set of lobster survey data without separating zeros and non-zeros and tried all four error models. For log-normal and log-gamma error models, a small constant of 0.01 was added to the records with zero values, and the resulting residual distributions were bimodal (not shown here). Those from Poisson and negative binomial models were also highly skewed (not shown here). The error distributions are closer to expected if the zero records are ignored. We, therefore, decided to use separate models for the non-zero catches and the probability of catching lobsters in this study.

With the non-zero encounter rates, all the four alternative error models were explored. If the over-dispersed Poisson error model fitted the data well, the variance in encounter rate should have been a linear relationship with the average encounter rates, whereas if the log-normal or log-gamma error model described the data well, the variance in encounter rate should have been proportional to the square of the average encounter rate. The negative binomial error model assumed that the variance of encounter rate is a function of both the average encounter rate and the square of the average catch rate (Punt et al., 2000). The fit of the log-normal/log-gamma error model was superior to the Poisson and negative binomial error models for both age groups, although the difference between the negative binomial and log-normal/log-gamma error models was marginal (Fig. 5). As log-gamma models resulted in more symmetric residual distributions than log-normal models, we used the log-gamma error model in the analysis of the non-zero encounter rates.

### 3.3. GLMs for the fixed station surveys

The survey data from the 50/41 fixed stations sampled between 1989 and 2002 were analyzed separately. The resulting gamma-based GLM fitted to the non-zero age 1+ lobster data included main effects: year, stratum, depth, and whether a chainman was used (Table 2). The

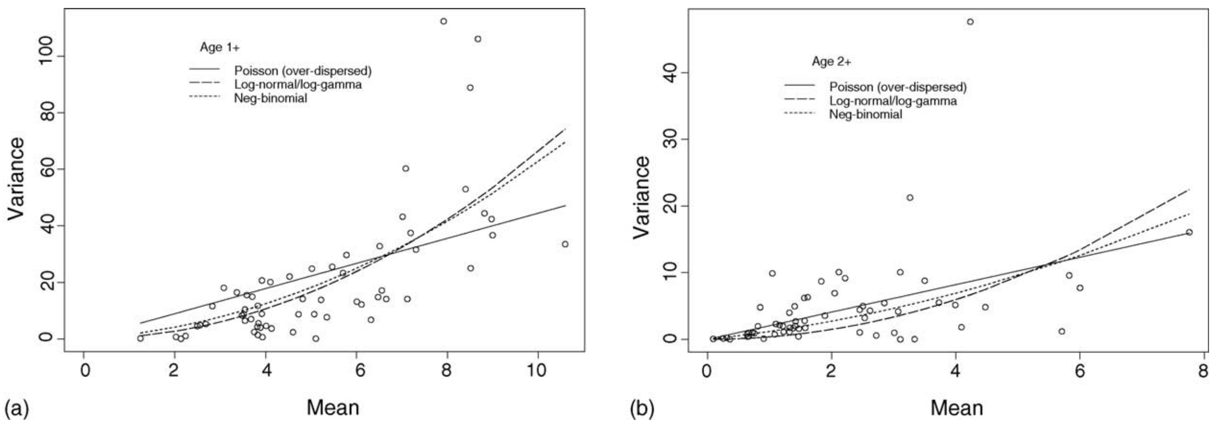


Fig. 5. Relationship between the variance in encounter rate and the average encounter rate for different distributions.

Table 2
Analysis of deviance table for the gamma-based GLMs

| Source of variation | d.f. | Deviance | Res. d.f. | Res. deviance | *F* | Pr(*F*) |
|---|---|---|---|---|---|---|
| Age 1+ | | | | | | |
| Null | | | 568 | 440.1 | | |
| Year | 13 | 38.5 | 555 | 401.6 | 5.23 | 0.000 |
| Stratum | 4 | 16.2 | 551 | 385.5 | 7.14 | 0.001 |
| Depth | 4 | 15.0 | 547 | 370.4 | 6.64 | 0.000 |
| Chain | 1 | 1.8 | 546 | 368.6 | 3.26 | 0.071 |
| Year:log(time) | 6 | 29.6 | 540 | 339.0 | 8.71 | 0.000 |
| Stratum:depth | 9 | 11.4 | 531 | 327.6 | 2.24 | 0.018 |
| Age 2+ | | | | | | |
| Null | | | 436 | 396.4 | | |
| Year | 13 | 75.6 | 423 | 320.8 | 8.48 | 0.000 |
| Stratum | 4 | 20.6 | 419 | 300.2 | 7.52 | 0.000 |
| Depth | 4 | 16.5 | 415 | 283.6 | 6.01 | 0.000 |
| Year:log(time) | 6 | 26.9 | 409 | 256.7 | 6.55 | 0.000 |

effect of using a chainman was only marginally significant, but its inclusion produced a lower AIC. There was also a significant interaction between stratum and depth and strong evidence of difference in slope of the linear regression on log(swimming-time) between years (Table 2). The model fit well as judged by the residual deviance (327.6 is a small value for a variate with 531 degrees of freedom).

Swimming time was expected to have a linear influence on encounter rate and was included in the model as a continuous variable after taking the logarithm. Swimming time was fixed at 20 min for 8 of the 14 survey years, and the linear regressions on log(swimming-time) were not possible for those years as indicated by d.f. = 6 (Table 2). The estimated slope coefficients ranged from 0.61 to 2.81. These positive coefficients indicated that the more time used, the higher the encounter rate. This is consistent with Eq. (5). When a diver took more time to swim a transect of a given length, they must have encountered more lobsters as spearing occurred proportionally.

Depth was recorded as a continuous variable in the data, but we used it as a factor variable in the GLM. This is mainly because the relationship between lobster count and depth was not simply linear or exponential, but bimodal. Using depth as a single continuous variable had very low capability of explaining the variation in lobster encounter rates. To capture the complex distribution pattern over depth, we divided depth into five irregular intervals: $\leq$4, 4–12, 12–18, 18–26, >26 m based on plots of encounter rate against depth.

Spatial and temporal factors in the GLM were of special interest to the understanding of variation in abundance. Spatial factors were stratum and depth, and the temporal factor was year only (Table 2). Effects of spatial factors described the spatial distribution and effects related to year showed changes in encounter rate between years. There was no interaction between these two types of factors (Table 2) suggesting that the spatial pattern of lobster distribution was consistent between years. However, there was a significant interaction between stratum and depth, and we concluded that each stratum had a different relationship between depth and encounter rate.

We extracted the temporal variation of non-zero encounter rates with the coefficients of the year factor and the year:log(time) interaction by inserting a mean swimming time into the regression functions in the GLM (Fig. 6). The encounter rates for recruiting (age 1+) lobsters exhibited a great fluctuation throughout the survey period with a clear decreasing trend after 1997.

The log-gamma GLM for fished (age 2+) lobsters was simpler than that for recruiting (age 1+) lobsters. Main factors of year, stratum and depth as well as the interaction between year and log(time) were all highly significant (Table 2). The model had a residual deviance of 256.7 with a residual degree of 409. It explained 35% of the data deviance, much higher than 26% for the age 1+ GLM (Table 2).

Non-zero encounter rates for fished (age 2+) lobsters were constructed with the same method as for the age

Table 3
Analysis of deviance table for the Bernoulli based GLMs

| Source of variation | d.f. | Deviance | Res. d.f. | Res. deviance | Pr(χ) |
|---|---|---|---|---|---|
| Age 1+ | | | | | |
| Null | | | 648 | 484.6 | |
| Year | 13 | 31.7 | 635 | 463.0 | 0.003 |
| Stratum | 4 | 7.2 | 631 | 445.8 | 0.127 |
| Depth | 4 | 9.7 | 627 | 436.1 | 0.045 |
| Chain | 1 | 4.7 | 626 | 431.4 | 0.030 |
| Year:log(time) | 6 | 26.3 | 620 | 405.0 | 0.000 |
| Depth:chain | 4 | 11.1 | 616 | 393.9 | 0.025 |
| Age 2+ | | | | | |
| Null | | | 648 | 820.1 | |
| Year | 13 | 103.4 | 635 | 716.7 | 0.000 |
| Stratum | 4 | 40.4 | 631 | 676.3 | 0.000 |
| Depth | 4 | 23.6 | 627 | 652.7 | 0.000 |
| GPS | 1 | 4.2 | 626 | 648.5 | 0.039 |
| Year:log(time) | 6 | 17.4 | 620 | 631.0 | 0.008 |

1+ group. The encounter rate in 1989 stands out from all the others and was about three times as high as the average of the remaining years (Fig. 6). A decreasing trend was also apparent, especially from 1998 to 2002.

For the Bernoulli model (Eq. (2)), we used a $\chi^2$-statistic to test for significance (Table 3) because the data of 0/1-measurements had a $\chi^2$-distribution in deviance. The model for recruiting (age 1+) lobsters selected year, stratum, depth, and use of chainman as significant main factors. Stratum was not significant, but was included because of its negative impact on AIC. This, however, suggested that the difference in probability of a non-zero age 1+ count was not obvious. Whether a chainman was used to control transect length had a significant effect on the probability of non-zero counts. Its coefficient indicated that deployment of a chainman reduced the probability of non-zero encounter rates because a time control of 20 min tended to have a longer transect than 500 m (Eq. (5)). With the increase in distance, a diver is likely to encounter more lobsters. The interaction between chainman use and depth was also significant and its ability to explain the data deviance was fairly high (Table 3). The effect of the logarithm of swimming time varied between years, a result similar to that found with the log-gamma GLM.

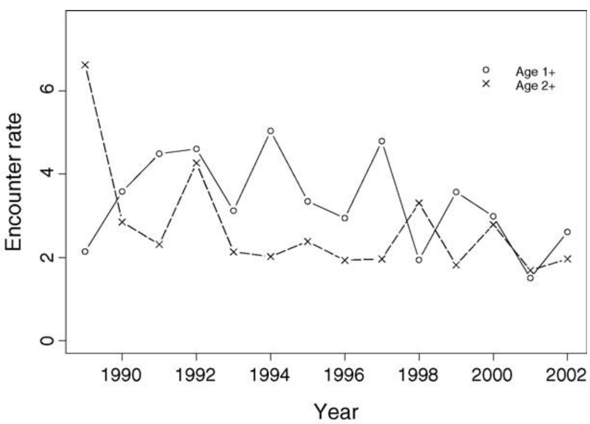


Fig. 6. Encounter rates (lobsters per 4 m × 500 m transect) estimated from the non-zero records with the log-gamma GLM.

The model explained 19% of the data variability with a residual deviance of 394 and a residual degree of 616 (Table 3). As none of the interactions between spatial and temporal factors were found to be significant, the probability of a non-zero age 1+ count was estimated from year-related terms. It remained very stable and close to 100% before 1998, but dropped slightly down to 91% in 2002 (Fig. 7).

The Bernoulli GLM for age 2+ lobsters was slightly different from that for recruiting (age 1+) lobsters (Table 3). All terms were highly significant except for whether GPS was used to measure distance. The real mechanism for the effect of GPS on probability is not apparent. The model explained 23% of the deviance, higher than the 19% for the age 1+ group (Table 3).

The probability of encountering an age 2+ lobster varied greatly from 42 to 100%, in contrast to that for the age 1+ group (Fig. 7). It decreased from 1989

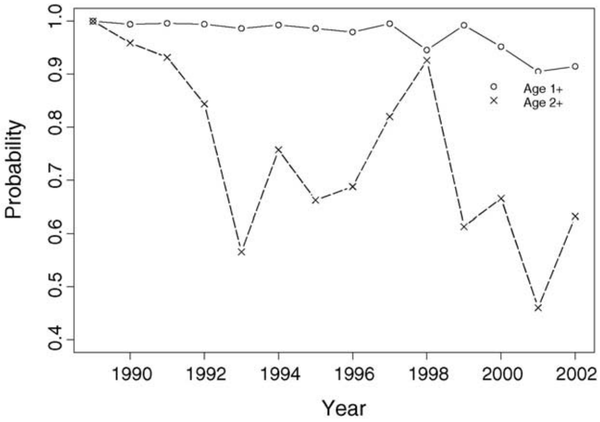


Fig. 7. Temporal trend in probability of encountering fished (age 2+) or recruiting (age 1+) lobsters extracted from the Bernoulli based GLM.

to1993, then recovered from 1995 to 1998 and dropped again after 1998.

### 3.4. GLMs for the random station surveys

We applied the same approach to model the data from the full-scale surveys in 1989 and 2002. As the length of transects was fixed in both years (using a transect line or chainman), there was no need to include factors indicating whether a chainman or GPS was used. Both age groups had the same log-gamma GLM. A significant difference in non-zero encounter rate was seen between the two years and different strata (Table 4). Depth was not found to have a significant impact on encounter rates.

The probability of non-zero counts assumed a more complex GLM. In addition to the significant terms of the log-gamma GLMs, depth was also found to be significant, together with the interaction between year and depth (Table 5). This meant that although the large-scale structure of the spatial distribution among strata did not differ between the 2 years, the small-scale pattern of the probability over depth changed with time.

### 3.5. Construction of abundance indices

The unconditional estimate of encounter rate in a specific year was computed by multiplying the probability of a non-zero count by the expected mean of non-zero encounter rates in that year. The encounter rates estimated from the fixed station surveys for 1989–2002 are shown in Fig. 8. The recruiting (age 1+) group was more variable, but fished (age 2+) lobsters exhibited a greater range of change. The encounter rate of recruiting (age 1+) lobsters was relatively stable before 1998; however, a decreasing trend was apparent after 1997. In contrast, fished (age 2+) lobsters had a consistent decrease over time. If 1989 was considered as an outlier, the decline in encounter rate over time for 2+ lobsters would seem less dramatic, however, the decreasing trend from 1998 to 2002 was still undisputable.

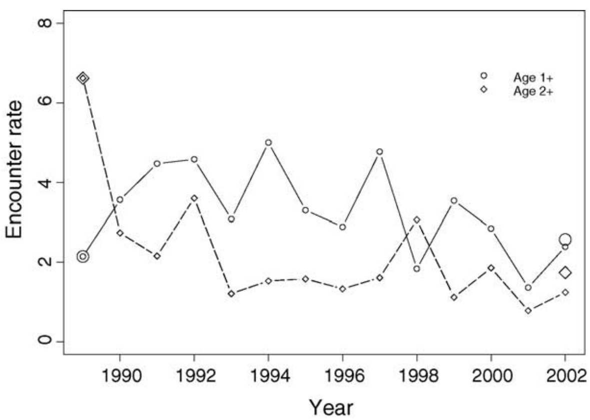


Fig. 8. Encounter rates (lobsters per 4 m × 500 m transect) estimated from the data of the 50/41 fixed stations from 1989 to 2002 with the large diamonds and circles indicating estimates from the benchmark surveys in 1989 and 2002.

Table 4
Analysis of deviance table for the gamma-based GLMs fitted to lobster survey data of 1989 and 2002

| Source of variation | d.f. | Deviance | Res. d.f. | Res. deviance | *F* | Pr(*F*) |
|---|---|---|---|---|---|---|
| Age 1+ | | | | | | |
| Null | | | 229 | 212.8 | | |
| Year | 1 | 5.6 | 228 | 207.2 | 8.99 | 0.003 |
| Stratum | 9 | 36.6 | 219 | 170.6 | 6.52 | 0.000 |
| Year:log(time) | 2 | 21.8 | 217 | 148.7 | 17.51 | 0.000 |
| Age 2+ | | | | | | |
| Null | | | 216 | 273.7 | | |
| Year | 1 | 67.9 | 215 | 205.8 | 89.52 | 0.000 |
| Stratum | 9 | 36.1 | 206 | 169.7 | 5.30 | 0.000 |
| Year:log(time) | 2 | 23.1 | 204 | 146.6 | 15.22 | 0.000 |

Table 5
Analysis of deviance table for the Bernoulli based GLM fitted to lobster survey data of 1989 and 2002

| Source of variation | d.f. | Deviance | Res. d.f. | Res. deviance | Pr($\chi$) |
|---|---|---|---|---|---|
| Age 1+ | | | | | |
| Null | | | 584 | 784.1 | |
| Year | 1 | 0.0 | 583 | 784.1 | 0.979 |
| Stratum | 11 | 95.2 | 572 | 688.9 | 0.000 |
| Depth | 5 | 10.7 | 567 | 678.1 | 0.057 |
| Year:log(time) | 2 | 26.8 | 565 | 651.3 | 0.000 |
| Year:depth | 4 | 9.8 | 561 | 641.5 | 0.044 |
| Age 2+ | | | | | |
| Null | | | 584 | 771.6 | |
| Year | 1 | 1.0 | 583 | 770.6 | 0.315 |
| Stratum | 11 | 97.2 | 572 | 673.4 | 0.000 |
| Depth | 5 | 13.3 | 567 | 660.0 | 0.020 |
| Year:log(time) | 2 | 29.5 | 565 | 630.6 | 0.000 |
| Year:depth | 4 | 8.6 | 561 | 622.0 | 0.073 |

The unconditional encounter rates for 1989 and 2002 estimated from the two-year benchmark surveys were contrasted with those from the fixed station surveys (Fig. 8). The estimates for recruiting (age 1+) lobsters were almost the same; however, those for fished (age 2+) lobsters differed considerably. Although the difference may not seem large in absolute value, it represents a 40% increase in encounter rate. Should the more comprehensive surveys in 1989 and 2002 produce more reliable estimates of stock abundance, the decreasing trend for fished (age 2+) lobsters would be less severe than seen in the estimates from the fixed station surveys. As the GLM can provide only relative estimates, the estimates from the random station surveys were rescaled to equal the 1989 estimates of the fixed station surveys for easy comparison.

### *3.6. Comparison between the GLM and design-based estimates*

With stratified random sampling, a designed-based approach simply estimates the stratum-weighted mean for each year. There is no specific need to consider issues such as distribution of the data, changes in spatial distribution, and other variables that may have impact/information on the encounter rate. We estimated stratum-area weighted mean encounter rates based on the 50/41 sites from 1989 to 2002 and contrasted them with the GLM estimates (Fig. 9). As the GLM-based estimates represent relative indices, we rescaled the design-based estimates to equal their mean to the mean of the GLM estimates over the study period.

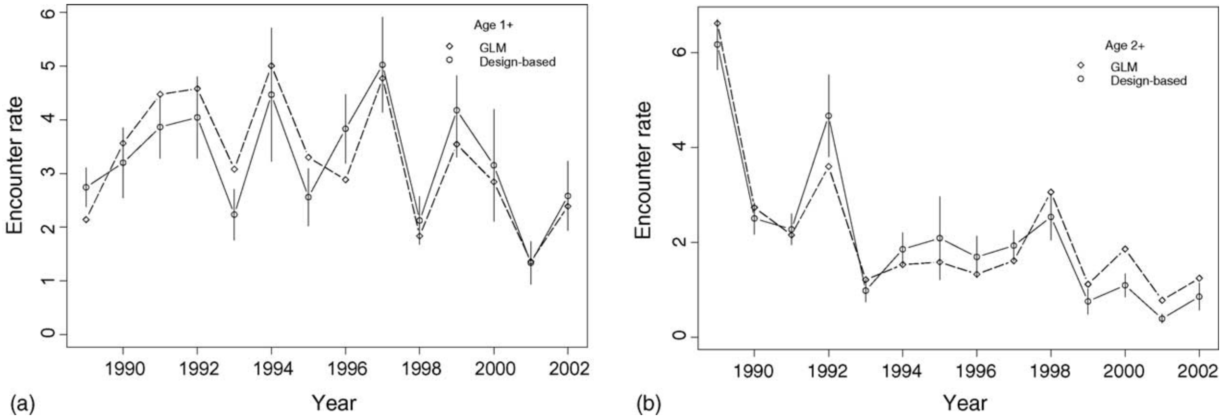


Fig. 9. Comparison between the GLM and design-based encounter rate estimates. The vertical lines indicate standard errors of the design-based estimates.

In general, the GLM estimates are within one standard error of the designed-based estimates with only three exceptions for fished (age 2+) lobsters (Fig. 9). However, there are some clear trends. For recruiting (age 1+) lobsters, the GLM estimates are higher than the design-based estimates before 1996, but lower after 1995. For fished (age 2+) lobsters, a reversed pattern exists, but less clear, but still exists. The number of fixed survey sites was reduced from 50 to 41 in 1996. This change in the number of sampling sites certainly has impacted on the results of designed-based methods, but less so on those of the GLM models. This is because GLM models fit spatial and temporal patterns and their interactions over the entire period and the year factor is able to capture major changes between years. GLM models are also flexible to include any variables that may have impact or information about lobster encounter rate for example swimming time and depth, and should provide more reliable estimation of the temporal changes in abundance. This is why more complex GLM methods were used in this study. However, a comprehensive comparison of the two approaches is not an easy task and beyond the scope of this study.

### 3.7. General remarks

The abundance indices constructed from the GLM models show considerable variation over time for both recruiting and fished lobsters (Fig. 8). This is likely due to the short life-span of this species and the relatively sensitivity of larval recruitment to variations in oceanographic conditions. The abundance indices for both age groups were comparatively low over the last few years (Fig. 8). This may well indicate that the lobster stock abundance dropped to a critically low level and that a comprehensive stock assessment should be done to diagnose the current status of the stock.

All GLMs used in this study, either for the non-zeros or for the probability of having a non-zero count, show a significant effect of stratum, but no interaction between the temporal factor of year and the spatial factor of stratum (Tables 2–5), indicating that a large-scale pattern among strata exists in lobster distribution and remained unchanged over the survey period. This is likely due to consistent habitat preferences of lobsters, as demonstrated for benthos by Van de Meer (1997). Further, extensive tag-recapture studies conducted in Torres Strait showed that most lobsters remained in the same reef system prior to the annual breeding migration (Moore and MacFarlane, 1984). Stratification of the survey was based on habitat distribution first and then revised according to the new data collected after the first full-scale survey in 1989 (Pitcher et al., 1992). However, the results from the stratified random surveys in 1989 and 2002 show that the small-scale distribution over depth does change between years (Table 5). This poses the question of the suitability of fixed station surveys for the construction of relative abundance indices for the Torres Strait lobster population.

This study focuses on the estimation of abundance indices, and only the temporal variation in encounter rates was presented. However, the large-scale pattern in lobster distribution can be easily estimated from the main effect of stratum. The small-scale distribution over depth is more complicated and involves interaction with year or stratum in some models (Tables 2–5). This kind of result would be of great interest to ecologists and those who study the relationship between species distribution and habitat.

The sampling design for a field survey to a large extent determines the interpretation and accuracy of the abundance estimates and how it changes over time. Van de Meer (1997) compared three survey designs for marine benthos: random, fixed and mixed. He found the mixed design had a smaller variance and greater power than the other two on the condition that there is on average a positive correlation between station means in different years. He then concluded that the mixed design, which randomly selected sample stations for the first year and then revisited them in following years, is the most appropriate design for a monitoring program for marine benthos, where the primary objective is detection of change in abundance. In the case of Torres Strait lobster surveys, not all stations randomly selected in first year were revisited in subsequent years, but only a sub-set of the stations were expert-selected and re-sampled. So, the design is a hybrid of Van de Meer's (1997) fixed and mixed designs. The similarity of the encounter rate estimates for 1989 and 2002 from the annual fixed stations of 1989–2002 to those derived from the full-scale surveys in 1989 and 2002 may to some extent prove the feasibility of monitoring abundance changes in the lobster fishery through surveying the ad hoc fixed stations. However, the difference seen in the abundance of fished (age 2+) lobsters (Fig. 8) and the fact that only 2 years were compared may suggest that caution should be exercised and further tests should be carried out in the future.

We found separate modeling for the non-zero encounter rates and the probability of encountering lobsters preferable. Stefansson (1996), Punt et al. (2000) and Ye et al. (2001) reached the same conclusion for the analysis of fishery log-book data, and Pennington (1983) and De la Mar (1994) made similar remarks for the analysis of survey data. The approach of separate modeling provides an analysis technique where many problems usually associated with zero values are alleviated. This includes issues such as those involving the definition of an appropriate coverage area for the analysis and those related to log transforming values that can be arbitrarily close to zero.

The number of lobsters a diver encounters is a function of lobster density and the area he/she searches, which is in turn determined by swimming time, current speed, the number of lobsters speared, etc. Without missing records, numbers of lobsters encountered can be directly modeled with a GLM, and abundance indices can be constructed from the coefficients of corresponding factors. No standardization is needed at all. The advantage of fitting a GLM to raw data is that information processing/integration is completed in a single comprehensive step, and no information will be lost. However, each years lobster survey experienced not only different designs but also many changes in survey implementation. As a result, variables were not measured consistently throughout the survey period. The high proportion of missing values can simply result in the model failing to fit. We, therefore, first imputed those missing values through multiple linear regressions based on standardized encounter rates. This apparently solved the missing data problem at the beginning of the analysis. However, it must be born in mind that an unprincipled imputation method may create problems (Little and Rubin, 1987).

Inconsistency in survey design has nevertheless created enormous difficulty for data analysis and might contribute towards biased results. The most notable was the change in the total number of survey sites and their selection. The 50/41 sites revisited in the abbreviated surveys were expert choices, driven by logistic and funding constraints. No consideration was given to the variability of encounter rates and the number of stations required in each stratum. With a fixed design, the estimated mean and variance of the change in abundance from a limited area are used to represent the whole area. The estimate of the mean for the whole area is then biased and the variance is underestimated (Van de Meer, 1997). When a spatial structure exists as it does in the lobster population (Tables 2–5), unstratified fixed station surveys are almost certain to produce biased estimates of the mean, particularly when some entire strata which have relatively lower or higher values are not included. However, the stability of spatial structure means that such a bias may be consistent over years. Where relative indices are concerned, consistent biases may cancel out each other, and the impact of non-random selection of survey stations may become unimportant. This may be the reason why fixed station surveys have proven suitable for the northern shrimp (*Pandalus borealis*) fishery-independent survey within the Skagerrak and Norwegian Deeps (Tveite, 2000) and for the collection of relative abundance data from commercial fishing vessels in Australia's southern shark fishery (Punt et al., 2002).

Finally, this study presents the construction of relative abundance indices for the lobster population in Torres Strait based on surveys of different designs. However, it is unreasonable to assume that the indices of relative abundance from these analyses are completely free from the effects of changes in survey design. We stress the importance of survey design to safeguard reliability and accuracy of abundance estimates. Future lobster surveys can benefit significantly from efforts to improve the coverage, balancing the number of sites among different strata, and maintaining design consistency over time, especially when unpredictable change in spatial distribution is probable.

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# Cost benefit of fishery-independent surveys: Are they worth the money?

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ABSTRACT

Fishery-independent monitoring is invariably more costly than fishery-dependent monitoring but is justified on the basis of the value of the data for effective management, or is viewed as the only valid approach for setting Total Allowable Catches (TAC). However, the cost-benefit of fishery-independent monitoring is rarely explicitly assessed. Development of an integrated fishery model for the Torres Strait tropical rock lobster (TRL) *Panulirus ornatus* fishery provided the opportunity to assess the relative value of different combinations of fishery survey methods. Annual fishery-independent pre-season and mid-season surveys were compared with fishery-dependent data collection. All three methods are currently carried out or have been in place in the recent past. Typically, short-lived highly variable species such as TRL require both recruit and spawner biomass surveys. Using CPUE data only, and not carrying out either the pre-or mid season fishery independent surveys, resulted in lower and considerably less precise TAC estimates. When conducting both fishery-independent surveys a positive cost benefit ratio was realised if additional catch to the CPUE-based TAC estimate was greater than 14.8 t (around 2% of TAC). TAC estimates based on independent fishery surveys were up to 20% greater than the model-predicted estimates using CPUE data alone. Including both independent fishery surveys returned a positive net present value over a 20 year timeframe even when randomly varying biomass, accounting for increasing survey costs, lower gross margins, and lower lobster prices.


## 1. Introduction

Improved management of many of the world's wild-caught fisheries has led to more sustainable practices and stable catches [1], and further rebuilding of overfished stocks has the potential to dramatically increase net economic gains from global fisheries [2]. Overfishing is not a universal issue and many of the world's fisheries, including Australia's, are sustainably fished due to robust scientific advice and management of their target catch and ecosystem impact [3]. In these fisheries, it is important subsequently to maximize their economic viability [e.g. [4]. Effective stock monitoring and assessment are both key to this outcome. However, it is essential that monitoring and assessments are cost-effective; particularly given that many fisheries are pro-actively moving to quota management and cost-recovery management systems [5].

There are two major sources of data available to provide an index of relative (or absolute) abundance for fishery stock assessments: fishery-dependent data and fishery-independent data. Fishery-dependent data includes catch and effort information collected by the fishing industry itself. Fishery-independent data is based on independent surveys and abundance and distribution data are generally collected by fishery management agencies.

Fishery-dependent data are invariably cheaper to obtain given that the information can be captured in the process of fishing. The data can be provided by the fishers themselves through paper or electronic logbooks or by an observer onboard the fishing vessels during the fishing operation. An advantage of these data is that they usually encompass greater spatial and temporal coverage than possible by independent survey. However, the data may be insufficient for thorough stock assessment for many reasons including; hyper-stability [6], spatial variability of fishing effort [7], variable fishing power [8] or simply through erroneous data collection. Even after standardisation it is possible catch per unit effort (CPUE) may not reliably index stock abundance [9].

The advantages of fishery-independent data are often stated but the cost-benefit of the data is rarely explicitly assessed. However, Hoshino et al. [10] were able to assess the cost-benefit of scientific survey information under an adaptive management procedure developed for the Japanese common squid fishery. To achieve an indicative coefficient of variation (CV) of 0.1 for the CPUE estimate, they determined a within-season assessment would be worth doing if it

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cost less than 1.28 billion yen per year. Fishery-independent data are invariably more expensive to attain per unit data coverage, if only because it involves employment of fisheries scientists to collect the data. Punt et al. [11], for example, showed the management-related benefits of fixed-station fishery-independent surveys for gummy shark, but did not estimate the cost-benefit ratio of this approach.

In a review of fisheries management, Caddy and Cochrane [12] highlighted the need for fishery monitoring systems that are both robust to inherent uncertainty and cost effective. Advancing this proposed need, Bentley and Stokes [13] developed a formal evaluation of alternative data collection regimes using a utility function to incorporate both costs and performance measures. They demonstrated the value of adaptive monitoring in a low-value, data-poor fishery in New Zealand. However, comparative estimates of assessment research to stock value are rare in the fisheries literature.

The tropical rock lobster (TRL) fishery in Torres Strait, Australia (Fig. 1) provides valuable income for the indigenous inhabitants and a small fleet of non-indigenous fishers [14]. Fishery-independent surveys of the population have been conducted annually since 1989 [15] to inform managers of relative stock abundance. The average annual ratio of the cost of stock monitoring and assessment research to gross value of the fishery catch is relatively high at ~2.5%, due primarily to its local importance to the indigenous inhabitants. More recently, commercial catch and effort statistics have been provided through compulsory logbooks. The age-structured fishery stock assessment model [16] fits to both CPUE data and fishery-independent data to determine stock status and total allowable catch (TAC). The development of the integrated model to estimate a TAC was done in response to a directive from the Australian government to move management of the TRL fishery from input controls to a quota managed system (QMS), and the fishery is currently in a transition period.

The cost of management-related research for this fishery could be greatly reduced by discontinuing the fishery-independent surveys but the outcomes of this change are unknown. However, it was possible to predict these outcomes using different data source inputs to the integrated model.

Generally, the aim of a fishery independent survey is to help reduce uncertainty in stock assessment results which will thus increase allowable harvest and revenues to the fishery [17]. The success of a survey achieving this relies on: risk adverse managers who set harvest levels to some fraction of the nominal target; the fraction has to be based on uncertainty in stock assessment results (with lower fractions and lower catches at higher levels of uncertainty); no direct linkage between recruitment and harvest (harvest this year has no effect on harvest next year); and the foregone catch has no value to the fishery as catch in another fishery.

In this paper, we use a simple net benefit approach to retrospectively assess the question of whether predicted increased revenues of assessments based on fishery-independent information offset the cost of the survey. A sensitivity analysis of the cost-benefit ratio of fishery-independent monitoring under different catch assumptions can be used to assist management of this small-scale but locally important fishery.

## 2. Methods

### 2.1. Fishery-independent data

Annual surveys of the TRL population in Torres Strait were instigated in 1990 following a broad-scale survey of lobster distribution and abundance in 1989 [15] involving 542 randomly-allocated stations. The annual stock surveys were conducted mid-year (June) and involved divers sampling a sub-set of the stations sampled in the benchmark 1989 survey. The design and implementation of the surveys changed over time due to funding and logistical constraints and Ye et al. [18] constructed consistent abundance indices using GLM standardisation of the historical data.

The annual surveys provided relative abundance indices for two lobster age-classes; sub-legal recruiting lobsters aged about 1.5 years (1+) and legal lobsters aged about 2.5 years (2+). Lobsters settle in Torres Strait around June each year following a ~6 month larval phase [19]. They live among the coral reefs for about 2 years. The 2+ lobster population emigrates to breed between mid-August and late-September each year [20]. The 2+ lobster population that migrates does so on the bottom of deep waters in the Torres Strait and effectively becomes unavailable for fishing during migration as trawling along the migration route is

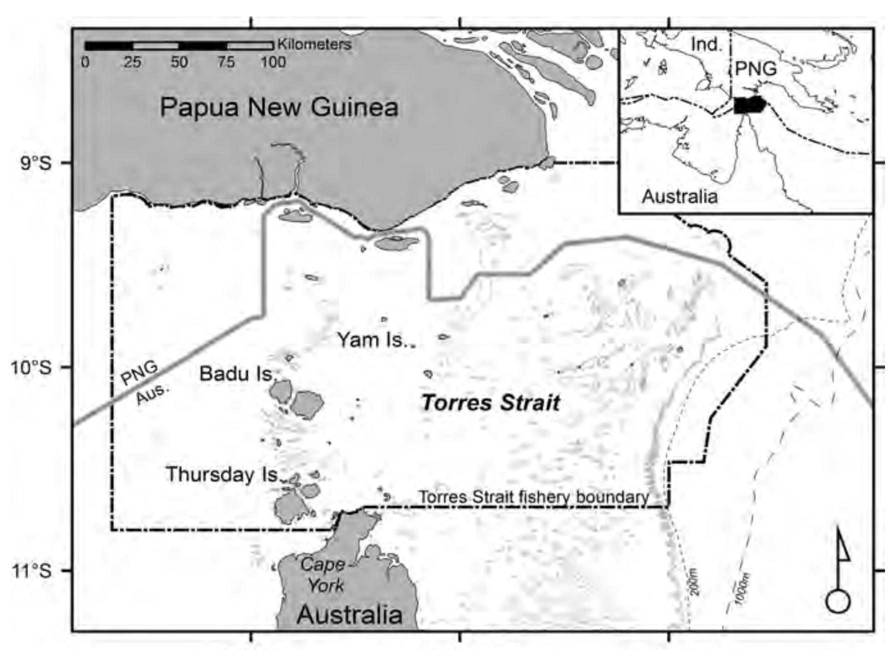


**Fig. 1.** Map of Torres Strait showing the international boundary of Australia and Papua New Guinea and the boundary of the tropical rock lobster (TRL) fishery.

no longer allowed in this fishery. Migrating lobsters were targeted by trawlers until the practice was banned in 1984 [21]. During the breeding migration, most 2+ lobsters leave Torres Strait principally to the Gulf of Papua; and do not return. The 2+ abundance indices, as measured before migration, provide data on the relative size of the spawner stock.

In response to the requirement for output controls, in 2005 a second annual recruit survey, conducted in November/December was instigated in addition to the ongoing spawner biomass surveys. The rationale for instigating an additional survey at the end of year was that it was closer to the season opening in December. As the survey was closer to the opening season it provided a higher level of accuracy and certainty in forecasts of stock in the following year. This further improved prediction of the TRL stock size as there is substantial inter-annual variability in recruitment, driven by environmental factors, some of which are not well understood.

The sampling protocol of the second surveys was consistent with that of the ongoing surveys but additional stations were included to improve precision of the recruiting lobster abundance estimate. The second surveys provided relative abundance indices for 1+ lobsters and recently-settled lobsters aged about 6 months old (0+). Very few 2+ lobsters were observed during the second surveys as most of the 2+ population would have emigrated to spawn at the time of the second survey.

The second surveys were discontinued in 2008 due to funding constraints. Hence, indices of abundance for 1+ and 2+ lobsters have been estimated from ongoing annual (hereafter termed first) surveys during 1989–2011, and indices of abundance for 0+ and 1+ lobsters have been estimated from a second annual survey during 2005–2008. Implementation of the QMS has also been delayed to date.

### 2.2. Fishery-dependent data

A compulsory logbook program was implemented in the TRL fishery in 1994 to monitor catch and effort of the non-indigenous sector; hereafter termed the TVH (transferable vessel holder) sector. This program provided a continuous source of CPUE indices that could be compared and contrasted with the fishery-independent indices. Due to a combination of a minimum size limit (115 mm tail length $\approx$90 mm carapace length) and closed season (October − November) >95% of the catch comprises of 2+ lobsters [16]. Hence, CPUE indices were comparable with the 2+ lobster abundance indices mainly from the first fishery-independent surveys, but not the 1+ lobster abundance indices obtained in the second survey (before it was stopped in 2008).

### 2.3. Fishery model TAC estimates

We used the age-structured fishery assessment model [22] which integrates both the fishery-independent and fishery-dependent data sources to enable stock status assessment and TAC recommendation. Details of the model are available in [22], and brief summaries of model equations and parameters used are provided in Tables 1 and 2 respectively. The model computes a recommended TAC based on a target fishing mortality rate applied to the estimated biomass. As the QMS has not been implemented to date, the annual TACs are currently used only as guides, but will be used for future quota allocation.

The assessment model includes first survey data for the period 1989–2011 and data from the additional second survey for the period 2005–2008. The model was used to retrospectively calculate illustrative second survey indices of abundance (1+ and 0+) (with error) for the "missing" years 2009−2011. The model-simulated second survey data were assumed to have the same observation errors and variances as the historic observed data. The 2010 lobster assessment model was then used to simulate what the effect might have been of having second survey data for years 2009 and 2010 on the TAC prediction for 2011 and preliminary TAC allocation for 2012. The latter is computed as the lower end of the TAC 75% confidence interval, to provide a "precautionary" estimate. Results are assessed both in terms of the difference in the TAC estimate as well as the associated uncertainty, as quantified by the CV and associated Hessian-based 90% confidence interval.

The model was used to retrospectively compute TACs for 2011 and 2012 for four data source scenarios (1) using the first survey and CPUE data (2) using the second survey and CPUE data (3) using both first and second survey data and CPUE data, and (4) using CPUE data only. These scenarios provided comparative TAC values to evaluate different allocations under future quota management. Comparison of the scenarios provided estimates of additional or reduced catch allocations with and without fishery-independent survey data.

### 2.4. Cost-benefit analysis

Our cost-benefit analysis was based on the simple premise that fishery-independent surveys would be economically justified when the profit attained due to an additional catch allocation estimated by the fishery model at least matched the survey cost and assuming that the fishery-independent survey outputs were incorporated by managers to set the TAC. All profits and costs were calculated in Australian dollars. Conversely a reduced allocation for a scenario would imply potential negative net benefit and survey costs would not be justified.

The actual annual 2011 research costs were (1) AUD$87,500 for the first survey only (2) AUD$140,000 for the second survey only and (3) AUD$175,000 for stock assessment and TAC estimation using CPUE data only. These costs were actual amounts drawn from research budgets for the client and included private vessel charter for the diver surveys, travel costs and employment of research staff required to undertake the current stock assessment and TAC estimation. A flow diagram illustrating the four data source scenarios for model TAC prediction are illustrated in Fig. 2.

The additional or lost TAC for each scenario was converted to revenue using the 2012 market price ($28 kg$^{-1}$) for live lobsters. This revenue was then converted to net profit by subtracting the operational cost of fishing estimated during recent management strategy evaluation research on the TRL fishery [23].

Net benefit ratios (NBR) were calculated for each scenario as the quotient of net profit and survey cost. Sensitivity of the NBRs to the estimate of gross margin share was assessed by plotting contours of NBR for a range of gross margin shares against additional catch. These plots also provided estimates of break-even additional catch required to cover the cost of the survey(s).

### 2.5. Net present value analysis

In reality, the additional or reduced catch amount is likely to vary each year relative to stock size and consequently catch. To avoid long run overestimation of the benefits of continuing or discontinuing fishery-independent surveys a NPV analysis was undertaken using a randomly generated series of annual additional catch amounts. The series was generated using the historic catch time series to scale the simulated variability in annual additional catches.

A series of 30 simulations with randomly assigned additional catch levels for six different scenarios using a 6% discount rate over a 20 year period were undertaken. For each of the scenarios the maximum survey costs as shown in Fig.2 were assumed. For the base case and the first 3 scenarios the additional catch each year was randomly varied between 0% and 100% of the maximum amount. In scenarios 5 and 6 the "additional" catch was also assumed to vary into the

**Table 1**
Summary of key model equations, and likelihood formulations used for fitting to survey and CPUE information.

| Description | Equation |
|---|---|
| Numbers-at-age $a$ in year $y$: ($a$=1) | $N_{y+1,a+1} = (N_{y,a}\, e^{-3M_a/4} - C_{y,a})\ e^{-M_a/4}$ |
| ($a$=2) | $N_{y+1,a+1} = (N_{y,a}\, e^{-M_a/2} - C_{y,a})\ e^{-M_a/2}$ |
| Number of recruits (defined as new 1-year old lobsters) at the start of year $y$ | $R_y = \left(\alpha B^{sp}_{y-1}/\beta + \left(B^{sp}_{y-1}\right)\right) e^{(\varsigma_y - (\sigma_R)^2/2)}$ |
| Catch by mass in year $y$ | $C_y = w_1^{land} N_{y,1} e^{-3M_a/4} S_{y,1} F_y^{1+} + w_2^{mid} N_{y,2} e^{-M_a/2} S_{y,2} F_y^{2+}$ |
| Model estimate of the exploitable ("available") component of biomass of 2+ lobsters | $B_y^{ex,2+} = w_2^{mid} S_{y,2} N_{y,2} e^{-M_a/2}$ |
| Contribution of the survey data to the negative of the log-likelihood function (after removal of constants) | $-\ell n\, L^{Surv} = \sum_i \sum_y \left[\ell n\left(\sigma_y^i\right) + \left(\varepsilon_y^i\right)^2/2\left(\sigma_y^i\right)^2\right]$ Where |
| | $I_y^i = \hat{I}_y^i \exp\left(\varepsilon_y^i\right)$ or $\varepsilon_y^i = \ell n\left(I_y^i\right) - \ell n\left(\hat{I}_y^i\right)$, $\varepsilon_y^i$ from $N\left(0, \left(\sigma_y^i\right)^2\right)$ |
| Standard deviation of the residuals for the logarithms of the observed CPUE and model-predicted abundance series | $\hat{\sigma}^s = \sqrt{(1/n_s)\sum_y \left(\ln I_y^s - \ln \hat{I}_y^s\right)^2}$ where $n_s$ is the number of data points for the CPUE abundance series $s$. |
| Sampling variance estimates for the survey index of abundance | $\left(\sigma_y^s\right)^2 = \ln\left(1 + (CV_y)^2\right)$ and the coefficient of variation ($CV_y$) of the resource abundance estimate for year $y$ is input |

**Table 2**
List of the model variables and parameters, which appear in Table 1 together with descriptions and values. All rate-related parameters have units yr$^{-1}$.

| **Variable** | **Description** | **Units** |
|---|---|---|
| $N_{y,a}$ | Number of lobsters of age $a$ at the start of year $y$ (which refers to a calendar year) | no. |
| $R_y$ | Recruitment (number of 1-year-old lobsters) at the start of year $y$ | no. |
| $M_a$ | Natural mortality rate on lobsters of age $a$ | yr$^{-1}$ |
| $C_{y,a}$ | Predicted number of lobsters of age $a$ caught in year $y$ | no. |
| $\alpha, \beta\ \varsigma_y, \sigma_R$ | Spawning biomass-recruitment relationship parameters, $\varsigma_y$ reflects fluctuation about the expected recruitment for year $y$, which is assumed to be normally distributed with standard deviation $\sigma_R$ | – |
| $B_y^{sp}$ | Spawning biomass at the start of year $y$ | MT |
| $w_a^{mid}, w_a^{land}$ | Mass of lobsters of age $a$ that are landed mid-year, and at the end of the third quarter respectively | MT |
| $S_{y,a}$ | Commercial selectivity (i.e. vulnerability to fishing gear) at age $a$ for year $y$ | – |
| $F_y$ | Fished proportion (of the 1+ and 2+ classes) of a fully selected age class | – |
| $I_y^i$, $\hat{I}_y^i = \hat{q}_s \widehat{N}_y^{survey}$ | Scaled survey abundance index for year $y$ and series $i$, and corresponding model estimate, where $\hat{N}_y^{survey}$ is the model estimate of survey numbers | no./yr$^{-1}$ |
| $\hat{q}_s$ | Constant of proportionality (catchability) for the survey | – |

negative. Only the variable that was different from the base case is indicated in the list below.

1. Base case: 50% profit margin – 70,000 kg maximal extra catch
2. 35,000 kg maximal extra catch
3. 25% profit margin
4. Price (starting at $28) and profit margin (starting at 50%) both falling by 2% each year
5. Extra catch was randomly varied between −15% and 100% of 70,000 kg.
   5a randomly varying catch as above and increasing the survey cost by 1% and 2% each year over a 20 year period.
6. Extra catch was randomly varied between -50% and 100% of 70,000 kg

## 3. Results

### 3.1. Fishery-independent data

Both recruiting (1+) and fished (2+) lobster density indices estimated from fishery-independent surveys were highly variable during 1989–2011 (Fig. 3). Density varied approximately five-fold for recruiting lobsters and over ten-fold for fished lobsters. Standard errors of the density estimates were also variable over the study period.

Trends in recruiting (1+) lobster density indices from the second annual surveys were consistent with those from the ongoing first surveys for years when both surveys were conducted (Fig. 3).

### 3.2. Fishery-dependent data

CPUE estimates from the TVH logbook program were consistently lower for years prior to 2002 (Fig. 3). There was a steep increase in CPUE from 2009 to 2011 culminating in a record high level. The temporal trend in CPUE roughly matched the trend recorded for 2+ lobsters from the first fishery-independent surveys until 2011. The corroboration of the two temporal trends provided some evidence that the estimates were indicative of actual abundance but the recent divergence suggested this may not always be the case.

### 3.3. Modelled fishery TAC recommendations

The model-predicted biomass estimates resulted in TACs that differed both in absolute magnitude and in the associated precision of the predicted values (see CVs in Table 3). There was a small difference only between the TAC predictions for the cases with and without a second survey, as expected on the basis of the good correlation between the first and second survey indices. However if this correlation breaks down in future, as might happen if there is variable growth or survival of recruits in the 5-month gap

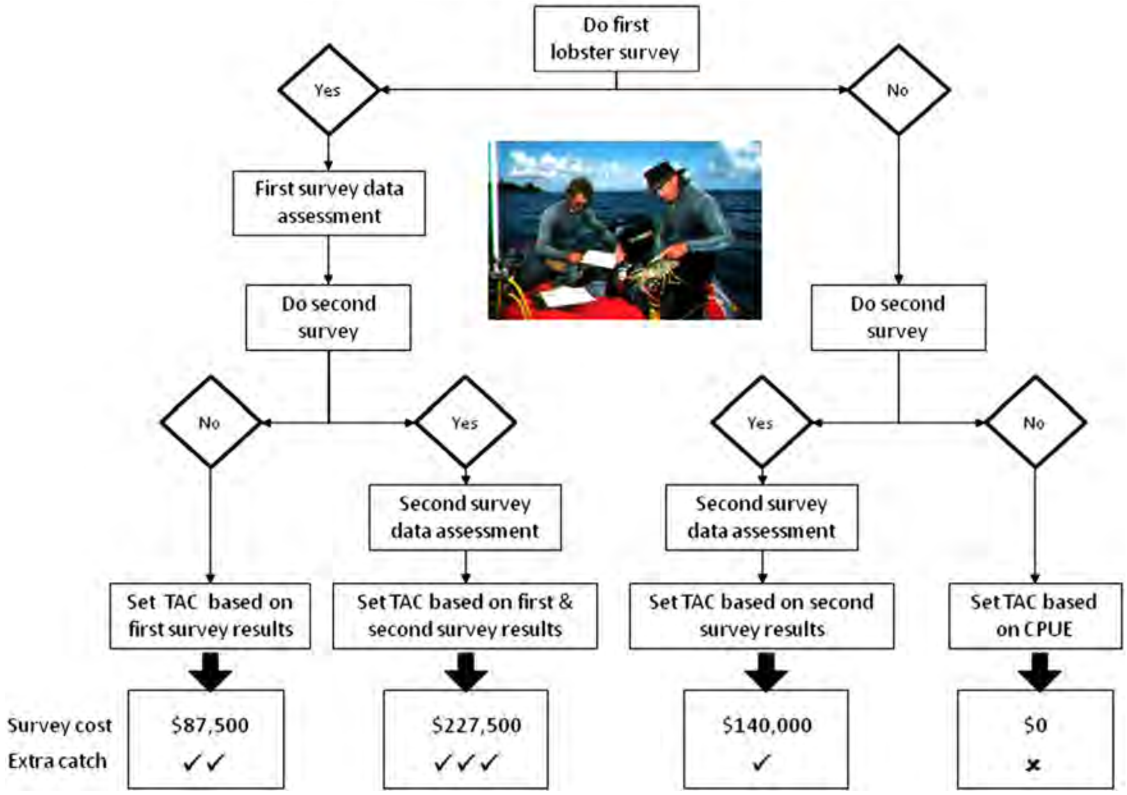


**Fig. 2.** Flow diagram illustrating the potential data source scenarios available to assess and set TACs for the TRL fishery; culminating in four survey cost and relative predicted additional catch outcomes.

between surveys then the predictions can be expected to diverge accordingly.

On the other hand, the predictions when using a model fitted to CPUE data only were substantially different, with a lower TAC prediction arising from the CPUE-only model. This is attributable to the conflict that exists between the fit to the survey and CPUE data, in particular because the 2009 CPUE data were substantially more negative that the 2009 survey data. This divergence can be attributed to the difference in spatial coverage of the fishery-independent versus fishery-dependent data. Moreover the fishery-dependent data only indexes one sector of the fishery, namely the TVH but not indigenous fishers. However in terms of catches these two sectors catch roughly the same amount annually, particularly in the more recent years.

### *3.4. Cost-benefit analysis*

The model-predicted TACs using the CPUE data only were all lower than the TACs using first survey data only, second survey data only and data from both surveys in 2011 and 2012 (Table 3). The break-even additional catch required to justify the cost of both surveys against using CPUE data only was 14.8 t at the average gross margin share level (50% or 0.5 in Fig. 4) used in this study. This value increases to ~40 t at the unlikely gross margin share value of 0.2. The break-even additional catches for second survey data only versus first survey data only and both surveys data versus second survey data only were 3.4 t, and 5.7 t respectively.

The net benefits of including the first survey data only, second survey data only or both surveys data varied. In some years carrying out only the second survey returned a higher TAC (as in 2012) whereas in other years adding both surveys returned a positive TAC (as in 2011) (Table 3).

### *3.5. Net present value*

The net benefit ratios for the different scenarios varied with additional or lost catch amount (Table 3) and gross margin share (Fig. 4). The average NPV (over the 20 year period) for the first survey only (the base case) was $3,165,000 (Fig. 5). In all of the 20 years the randomly assigned additional catch level returned a positive NPV. In scenarios 2, 3 and 6 (Fig. 5) the randomly assigned additional catch levels returned a negative NPV in 6, 9, and 14 of the 20 years but the average NPV was positive overall. Scenario 5a also returned a positive NPV for 29 of 30 simulations for both a 1% and 2% increase in the survey cost.

## 4. Discussion

The imperative to maximize the cost-benefit of a stock assessment protocol is likely strongest for low value fisheries such as the TRL fishery described here, mainly because the low value of the fishery does not warrant an expensive research budget. However, this research shows that relatively expensive monitoring and assessment research can be justified by even small increases in additional catch allocations.

The costs used in this cost-benefit assessment are based on actual recent research budgets. The most significant cost in the TRL research budget is private vessel charter. However, there are many ways to reduce the cost of fishery-independent research without compromising the accuracy or precision of the results. In many cases, including the TRL fishery, in-kind support from fishers can substantially lower operational costs. The economic incentive for such in-kind support could be strengthened by making explicit the catch ranges over which a positive cost-benefit ratio is achieved, as

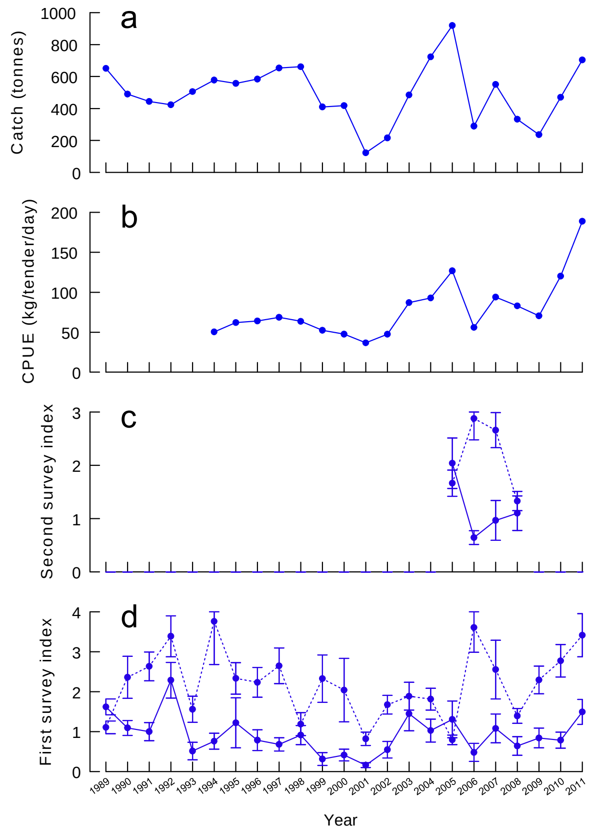


**Fig. 3.** Model data sources used to estimate TAC for the TRL fishery (a) commercial catch (b) CPUE of the TVH (transferable vessel holder) fleet (c) second survey abundance indices; recruiting lobster (1+) indices denoted by the dashed line and recently-settled lobster (0+) indices denoted by the solid line and (d) first survey abundance indices; recruiting lobster (1+) indices denoted by the dashed line and fished lobster (2+) indices denoted by the solid line. Error bars represent one standard error.

**Table 3**
Model-predicted TAC (tonnes live weight) estimates and coefficients of variation for the TRL fishery for four separate data source scenarios.

| Scenario | Year | TAC (t) | CV | Difference from first survey only | Difference from second survey only | Difference from both surveys |
|---|---|---|---|---|---|---|
| First survey only (base case) | 2011 | 803 | 0.27 | | | |
| Second survey only | 2011 | 789 | 0.22 | −14 | | |
| Both surveys | 2011 | 816 | 0.21 | 13 | 27 | |
| CPUE only | 2011 | 675 | 0.36 | −128 | −114 | −141 |
| First survey only (base case) | 2012 | 532 | 0.29 | | | |
| Second survey only | 2012 | 626 | 0.24 | 95 | | |
| Both surveys | 2012 | 602 | 0.22 | 70 | −24 | |
| CPUE only | 2012 | 528 | 0.36 | −4 | −98 | −74 |

done in this current study. Importantly, in this artisanal fishery, traditional fisher participation could encourage an exchange of information between scientists and local people and ultimately the maintenance of local ecological knowledge, thus also meet social and cultural objectives.

To achieve economic objectives fishery managers require predictions that are as precise as possible. Precision is based on an optimal trade-off between bias (approximation error) and variance (errors in estimating parameter values from the limited data available) as the errors of prediction are influenced by both. In other words, whether a survey should be included in the stock assessment or not depends on how much the model can be improved in estimating life history and fishery parameters.

The key motivation for using multiple data sets (i.e. both fishery independent and fishery dependent data), that is to reduce the variance of the estimable parameters and thus reducing the error of the estimated TAC, is met in this study. Our results confirm a substantial improvement in the precision of model predictions in response to adding one and then two fishery-independent surveys, with approximately 25% and 40% reductions in the associated coefficient of variation respectively (Table 3). The benefit of the higher, more accurate, yet constraining TAC is directly translatable into higher catches and converted into increased fishery profitability. This result holds even when random variations in catches are introduced in the model that estimates the NPV of the different survey approaches over a 20 year period.

A main driver for increasing the accuracy and precision of the estimated TAC for the fishing year ahead, is to reduce the need for a conservative TAC. Fishery stocks and TAC forecasts can be imprecise due to the inherent variability of environmental influences [24]. Given the inherent uncertainty there is an imperative to err on the side of caution for most fisheries using harvest strategies and setting TACs at lower confidence limits [25]. Following global fishery collapses the call for conservative TACs is further supported by the intense scrutiny of scientific advice [26], and a precautionary approach is invariably seen as politically responsible.

The importance of well-designed, independent surveys to complement CPUE data for highly aggregatory multi-sector stocks is well recognised [5]. There are clear benefits to conducting both spawner biomass and recruit surveys for highly variable recruit-driven species such as the South African jointly managed anchovy *Engraulis encrasicolus* and sardine *Sardinops sagax* pelagic fishery. An initial conservative anchovy TAC is set at the start of the year, together with an associated initial sardine total allowable bycatch (TAB) based on survey results. A May recruitment survey is then conducted later in the year [27], on the basis of which additional catch may be allowed [28].

This contrasts with the lower frequency of surveys that may be necessary to reliably predict stock size and productivity for longer-lived more stable species. For example, for the longer-lived Australian western rock lobster *Panulirus cygnus*, a puerulus settlement index is used to predict catches as much as four years in advance [29].

The roughly single-cohort nature of the TRL fishery is unusual amongst lobster fisheries. For the short-lived single-cohort variable-recruitment TRL fishery there is pressure to optimally utilise the stock annually given lobsters emigrate out of the fishing zone to breed each year and there is no alternative use and value of the stock that migrates (other than a small additional contribution to spawning biomass). The argument for annual surveys in this fishery is two-fold: firstly, the value of the stock will be optimised and, secondly, the highly variable nature of this fishery increases the importance of annual assessments to guard against both overfishing and under-fishing.

An important argument aside from the compelling economic benefits of the at-first impression of high fishery-independent survey costs, evident by the positive benefit cost ratio under different and extreme scenarios, is the fact that this fishery is shared by an

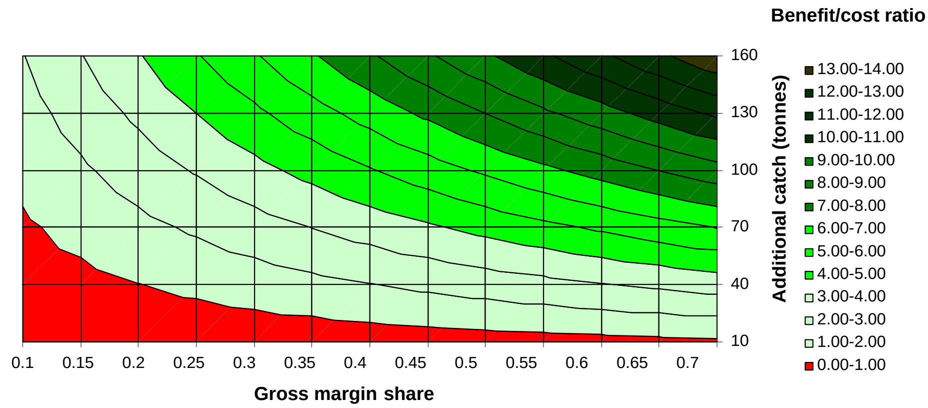


**Fig. 4.** Contour plot of benefit cost ratio estimates for gross margin share against additional catch for a model-predicted TAC scenario that includes the cost of both first and second annual surveys ($227,500), against a reference of using CPUE data only. The red portion indicates the minimum additional catch required to at least match the cost of the surveys. The model-predicted additional catches for this scenario were 141 t and 74 t in 2011 and 2012 respectively. At gross margin share of 0.55 the break-even additional catch estimate was 14.8 t.

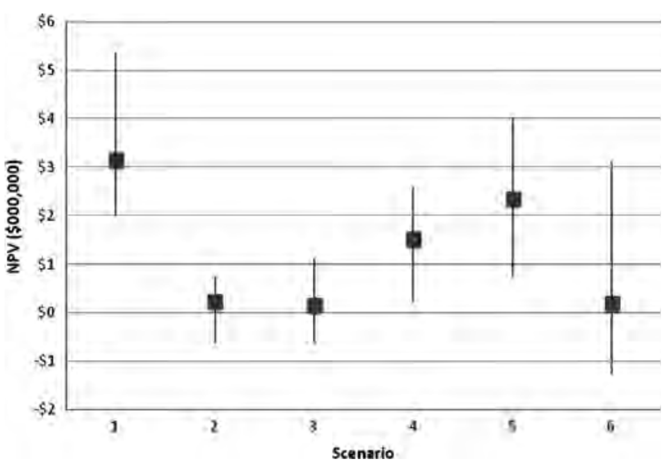


**Fig. 5.** Net present value estimates for six data source scenarios for the TRL fishery with a 20 year domain.

indigenous and non-indigenous sector. Only non-indigenous (TVH) CPUE data are currently used for the TRL fishery stock assessment and TAC estimation, as the indigenous sector is monitored by a voluntary docket book program and data are incomplete. Should the fishery move to a QMS system in the future with increased allocation to the indigenous sector, expectations are that a mandatory monitoring of all fishing will be required. However, due to uncertainties around the exact features of future QMS management and feasibility of accurately monitoring indigenous catches (even if mandatory) suggest caution should be taken in relying on catch data only. Fishery-independent monitoring systems become more valuable with increased length of the series, and discontinuation of these series can have economic repercussions as per the example presented here. Even though the recent indigenous and non-indigenous CPUE time series show similar trends it is possible that the loss of the certainties inherent in the non-indigenous fishery dependent CPUE data may affect precision in TAC predictions the future (eg. such as due to changes in allocation).

The results of the net present value analysis were robust to alternative resource outcomes trialled as well as across the 30 simulations with randomly assigned additional catch levels under each of six different scenarios. The results were based on simulations replicating historic levels of variability, but serially correlated years of good or poor recruitment were not simulated. Even though this could bias the results in the short-term, it is less important when averaged over 20-year NPV projections. Moreover, over the four-year period for which there were historic second survey data, there was a good correspondence between the first and second survey. This will magnify the extent of the predicted benefits of adding a second survey, with the latter functioning to update TAC recommendations in a roughly linear manner. This relationship may break down if there is a major environmental impact affecting the resource in the months between the surveys.

We concede that the research budget for the TRL fishery stock assessment is not available for most small-scale fisheries, particularly in developing countries. Even though the Australian Federal and State governments invest in sustainably managing fisheries, it is not our intention in this research to justify current or any future level of expenditure. This analysis simply demonstrates the net cost benefit ratio and NPV of different combinations of fishery independent and fishery dependent data sources in a fishery with a variable stock that is shared between an indigenous and non-indigenous sector. More complex and sophisticated methods could be used to rigorously derive a cost-benefit analysis, but there is considerable value in simple analyses to illustrate the potential benefits of the different fishery monitoring and assessment approaches. This approach can be easily applied to other both short and long-lived species and multi-species fisheries and has the potential to inform managers on the necessary rigor and cost to maximize overall profit whilst maintaining sustainable levels of exploitation.

## Acknowledgments

This work was funded by the CSIRO and the Australian Fisheries Management Authority (AFMA). We thank AFMA fishery managers Annabel Jones and Shane Fava, Torres Strait Regional Authority (TSRA) and industry representatives, as well as the TRL RAG members for their inputs and insights over the years. Mr. Nokome Bentley provided expert advice and recommendations during development of the fishery model used in this research. Our study is underpinned by 25 years of survey data and we thank the dedicated CSIRO divers.

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| TRL Fishery closed | | TRL Fishery open | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Oct** | **Nov** | **Dec** | **Jan** | **Feb** | **Mar** | **Apr** | **May** | **Jun** | **Jul** | **Aug** | **Sep** |
| | Pre-season survey conducted | Season opens 1-Dec | | | | | | | | | |
| | | PZJA determines a start of season catch limit of 200 tonnes which applies from 1-Dec to 28-Feb. Each of the 1 million quota units is worth 200 grams | | | | | | | | | |
| | | TRL RAG recommend a preliminary RBC | TRL RAG and Working Group recommend final RBC. Australia and PNG agree on shares of the RBC | | PZJA determines a final TAC by 1-Mar | | | | | | |

**Definitions**

Start of season catch limit is set at the start of the season to

Recommended biological catch (RBC) is the total catch of TRL that can be sustainably taken across all fishing sectors (e.g. commercial, traditional, recreational) – derived from the application of the empirical harvest control rule.

Total allowable catch (TAC) is Australia's share of the RBC as agreed with PNG each season.

| TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG) | MEETING 25<br>11-12 December 2018 |
|---|---|
| **PRELIMINARIES**<br>**Out-of-session correspondence** | **Agenda Item 1.5**<br>**For Information** |

## RECOMMENDATIONS

1. That the RAG **NOTE** the correspondence sent out-of-session since the last TRLRAG meeting held on 18-19 October 2018.

## BACKGROUND

2. The following correspondence was circulated out-of-session since the last TRLRAG meeting held on 18-19 October 2018 (TRLRAG24). Copies of this correspondence can be requested at any time from the TRLRAG Executive Officer.

| Date | Item |
|---|---|
| 30 October 2018 | AFMA circulated a media release from the Protected Zone Joint Authority (PZJA) regarding the PZJA's intention to have the TRL Fishery Management Plan in place by 1 December 2018 and to consider implementing catch share splits between the TIB and TVH sectors for the coming 2018/19 fishing season. |
| 31 October 2018 | AFMA circulated the draft meeting record for the TRLRAG meeting held on 18-19 October 2018, to Members for comment. |
| 2 November 2018 | AFMA circulated the draft TRL Five Year Research Plan to TRLRAG members as an attachment to the draft meeting record circulated on 31 October 2018. |
| 16 November 2018 | AFMA wrote to all RAG members confirming the TRLRAG meeting to be held on 11-12 December 2018 and noting key agenda items for consideration. AFMA also advised the meeting of the TRLRAG data sub-group be postponed until early 2019. |
| 27 November 2018 | AFMA circulated a Protected Zone Joint Authority (PZJA) communique detailing their agreement to determine a quota management plan for the TRL Fishery and to apply sectoral catch shares for the 2018/19 fishing season. |
| 29 November 2018 | AFMA circulated the draft agenda for the TRLRAG meeting to be held on 11-12 December 2018. |

| TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG) | MEETING 25<br>11-12 December 2018 |
|---|---|
| **UPDATES FROM MEMBERS**<br>**Industry members** | **Agenda Item 2.1**<br>**For Information** |

**RECOMMENDATIONS**

1. That the RAG **NOTE** updates provided by industry members.

**BACKGROUND**

2. Verbal reports are sought from industry members under this item.
3. It is important that the RAG develops a common understanding of any strategic issues, including economic, fishing and research trends relevant to the management the TRL Fishery. This includes within adjacent jurisdictions. This ensures that where relevant, the RAG is able to have regard for these strategic issues and trends.
4. RAG members are asked to provide any updates on trends and opportunities in markets, processing and value adding. Industry is also asked to contribute advice on economic and market trends where possible.

| TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG) | MEETING 25<br>11-12 December 2018 |
|---|---|
| **UPDATES FROM MEMBERS**<br>**Scientific members** | **Agenda Item 2.2**<br>**For Information** |

**RECOMMENDATIONS**

1. That the RAG **NOTE** updates provided by scientific members.

**BACKGROUND**

2. Verbal reports are sought from scientific members under this item.
3. It is important that the RAG develops a common understanding of any strategic issues, including economic, fishing and research trends relevant to the management the TRL Fishery. This includes within adjacent jurisdictions. This ensures that where relevant, the RAG is able to have regard for these strategic issues and trends.
4. Scientific members are asked to contribute advice on any broader strategic research projects or issues that may be of interest to the Torres Strait in future.

| | |
|---|---|
| **TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG)** | **MEETING 25**<br>**11-12 December 2018** |
| **UPDATES FROM MEMBERS**<br>**Government agencies** | **Agenda Item 2.3**<br>**For Information** |

**RECOMMENDATIONS**

1. That the RAG:
   a. **NOTE** the update provided by AFMA below;
   b. **NOTE** a verbal update will be provided by the QDAF and TSRA.

**AFMA UPDATE**

*TRL Management Plan*

2. On 26 November 2018, having considered outcomes of consultation, the Protected Zone Joint Authority (PZJA) decided to determine the *Torres Strait Fisheries (Quotas for Tropical Rock Lobster (Kaiar)) Management Plan 2018* (the Management Plan) and to amend the *Torres Strait Fisheries (Tropical Rock Lobster) Management Instrument 2018* (the Instrument).
3. The Management Plan and amendments to the Instrument came into force for the 2018/19 fishing season starting on 1 December 2018.
4. These decisions mean that, unless delayed by legal appeals, a quota management system will be fully operational in the TRL Fishery for the 2019/20 fishing season. A review of existing PZJA licencing policies and management arrangements, including input controls, will be conducted periodically after the quota management system is operational.
5. Copies of the Management Plan and amended Instrument along with a supporting guide describing how the Management Plan will work can also be found on the PZJA website at www.pzja.gov.au.
6. AFMA also wrote to all TRL Fishery licence holders on 28 November notifying them of these decisions and key management arrangements for the 2018/19 fishing season. A copy of this letter is provided at **Attachment 2.3a**.

*Management arrangements for the 2018/19 fishing season*

7. As the TRL Fishery undergoes the transition to a fully operational Management Plan, some key management arrangements that will apply in the 2018/19 season follow.

*Sectoral split*

8. Separate total allowable catch (TAC) shares will be implemented on an interim basis for the Traditional Inhabitant and Transferable Vessel Holder (TVH) sectors:
   a. Traditional Inhabitant sector – will be able to take a 66.17 per cent share of the TAC. This will be exclusively available to all Traditional Inhabitant Boat (TIB) licence holders. If all of this catch is taken by TIB licence holders before the end of the fishing season, a notice will be issued requiring fishing by this sector to cease.
   b. TVH sector – the remaining 33.83 per cent of the TAC will be individually apportioned to TVH licence holders, via licence conditions, in accordance with individual provisional allocation notices dated 1 October 2007. The TVH licence holders will be able to trade within the sector. Once TVH licence holders have exhausted their individual portion, including any leased quota, they will be required to cease fishing.

Each TVH licence holder will receive a letter outlining the licence condition setting their portion of the TAC. This portion may not reflect the allocation of quota under the Management Plan, which will be subject to a catch verification and appeals process.

*Interim and final TACs*

9. In order to give effect to the sectoral split, the PZJA further agreed to open the 2018/19 fishing season with an interim TAC of 200 tonnes. This decision is based on advice received from the TRL Resource Assessment Group and TRL Working Group, which advised that an interim TAC derived from the maximum annual catch amount over the years 2005-2018 for the period 1 December and end of February should be implemented.

10. This means that, from the opening of the 2018/19 fishing season:

    a. Traditional Inhabitant sector – can take a combined total of 132.34 tonnes of TRL.

    b. TVH sector – can take the amount of TRL specified in their individual licence conditions. The total amount that can be taken by the TVH sector will not be more than 33.83 per cent of the TAC.

11. The interim TAC will apply until a final TAC for the 2018/19 fishing season can be agreed. A final TAC is expected to be decided in early March 2019 and will follow the consideration of the updated stock assessment to be undertaken by CSIRO (including the results of the November 2018 pre-season survey), consultation with the TRL RAG and TRL Working Group and having regard to Australia's obligations under the Torres Strait Treaty.

*Moon-Tide Hookah Closures*

12. The PZJA also reaffirmed existing management controls currently applied to the TRL Fishery, to be implemented under the Instrument and licence conditions. This includes periodic closures to the use of hookah gear for three days either side of the full or new moon each month based on the largest difference between high and low waters.

13. The use, possession or control, on a boat, of hookah gear to take, process or carry TRL will not be permitted during the 2018/19 fishing season during the moon-tide hookah closure periods shown in the calendar (dated 28 November 2018) provided at **Attachment 2.3b**. The first scheduled moon-tide hookah closure period starts on 17 February 2018.

14. These moon-tide hookah closures are in addition to the hookah closure period from 1 December and 31 January each fishing season. Free-diving, lamp fishing and traditional fishing are permitted during all hookah closure periods.

*ABARES Fishery Status Report*

15. Each year, the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) compiles fishery status reports which provide an independent assessment of the biological status of fish stocks and the economic status of fisheries managed, or jointly managed, by the Australian Government (Commonwealth fisheries).

16. The ABARES *Fishery Status Reports 2018* were released on 28 September 2018 and summarise the performance of these fisheries in 2017 and over time, against the requirements of fisheries legislation and policy. The reports assess all key commercial species from Australian Government managed fisheries and examines the broader impact of fisheries on the environment, including on non-target species.

17. In summary, the biological status for the Torres Strait Tropical Rock Lobster Fishery has been assessed for the 2017 period as follows:

| Biological Status | Fishing mortality | Biomass | Additional comments |
|---|---|---|---|
| Tropical Rock Lobster | Not subject to overfishing | Not overfished | Current catches equate to fishing mortality rates below the target and |

| | | | |
|---|---|---|---|
| | | | limit reference points. Spawning stock biomass is above the target level. |
| **Economic Status** | Net economic returns (NER) movement in 2016-17 remain uncertain. A decrease in effort in the fishery in 2016-17 suggests a reduction in fishing costs, but this occurred with a fall in gross value of production. | | |

18. ABARES fishery status reports can be accessed on the ABARES website at: http://www.agriculture.gov.au/abares/publications/display?url=http://143.188.17.20/anrdl/DAFFService/display.php?fid=pb_fsr18d9abm_20180928.xml

*Sea surface temperatures*

19. Sea surface temperatures (SSTs) are currently below the coral bleaching threshold. The Australian Institute of Marine Science (AIMS) monitors sea surface temperatures to identify the risk of bleaching events (**Attachment 2.3c**). Reports can be accessed on the AIMS website at https://www.aims.gov.au/docs/research/climate-change/coral-bleaching/predicting-events.html.

20. Since 1970 the SST in the Coral Sea has consistently been above the long term average (data from 1900 to 2017).

21. The El Nino event from 2015/16 was more intense than previous events in recent history. The impacts to the TRL Fishery include increased mortality of cage-held lobsters and increasing coral mortality that may result in a reduction of suitable habitat. The influences on the larval phases of TRL are poorly understood.

22. SST information is also monitored by some fishers. If there is a spike in temperature the TRL held in cages or tanks will be monitored more closely (2 to 3 times a day) and they will be tailed or frozen whole if they are weak or not a suitable grade for live product.

23. AFMA, through AIMS, will continue to monitor SSTs this season.

28 November 2018

Dear Torres Strait Tropical Rock Lobster Fishery licence holder

**Introduction of the Tropical Rock Lobster Fishery Management Plan and Key Management Arrangements for the 2018/19 Fishing Season**

I am writing to inform you that on 26 November 2018, having considered outcomes of consultation, the Protected Zone Joint Authority (PZJA) decided to determine the *Torres Strait Fisheries (Quotas for Tropical Rock Lobster (Kaiar)) Management Plan 2018* (the Management Plan) and to amend the *Torres Strait Fisheries (Tropical Rock Lobster) Management Instrument 2018* (the Instrument).

The Management Plan and amendments to the Instrument will come into force for the 2018/19 fishing season starting on 1 December 2018.

These decisions mean that, unless delayed by legal appeals, a quota management system will be fully operational in the Torres Strait Tropical Rock Lobster Fishery (TRL Fishery) for the 2019/20 fishing season. A review of existing PZJA licencing policies and management arrangements, including input controls, will be conducted periodically after the quota management system is operational.

Please find enclosed copies of the Management Plan and amending Instrument along with a supporting guide describing how the Management Plan will work. Further information can also be found on the PZJA website at www.pzja.gov.au.

**Management Arrangements for the 2018/19 fishing season (in line with the Instrument)**

The 2018/19 fishing season for the TRL Fishery will commence on 1 December 2018. In the interim, as the TRL Fishery undergoes the transition to a fully operational Management Plan, some key management arrangements that will apply this season are as follows.

*Sectoral split*

Separate total allowable catch (TAC) shares will be implemented on an interim basis for the Traditional Inhabitant and Transferable Vessel Holder (TVH) sectors:

- **Traditional Inhabitant sector** – will be able to take a 66.17 per cent share of the TAC. This will be exclusively available to all Traditional Inhabitant Boat (TIB) licence holders. If all of this catch is taken by TIB licence holders before the end of the fishing season, a notice will be issued requiring fishing by this sector to cease.

- **TVH sector** – the remaining 33.83 per cent of the TAC will be individually apportioned to TVH licence holders, via licence conditions, in accordance with individual provisional allocation notices dated 1 October 2007. The TVH licence holders will be able to trade within the sector. Once TVH licence holders have exhausted their individual portion, including any leased quota, they will be required to cease fishing. Each TVH licence holder will receive a letter outlining the licence condition setting their portion of the TAC. This portion may not reflect the allocation of quota under the Management Plan, which will be subject to a catch verification and appeals process.

*Interim and final TACs*

In order to give effect to the sectoral split, the PZJA further agreed to open the 2018/19 fishing season with an interim TAC of 200 tonnes. This decision is based on advice received from the TRL Resource Assessment Group and TRL Working Group, which advised that an interim TAC derived from the maximum annual catch amount over the years 2005-2018 for the period 1 December and end of February should be implemented.

This means that, from the opening of the 2018/19 fishing season:

- **Traditional Inhabitant sector** – can take a combined total of 132.34 tonnes of TRL.

- **TVH sector** – can take the amount of TRL specified in their individual licence conditions. The total amount that can be taken by the TVH sector will not be more than 33.83 per cent of the TAC.

The interim TAC will apply until a final TAC for the 2018/19 fishing season can be agreed. A final TAC is expected to be decided in early March 2019 and will follow the consideration of the updated stock assessment to be undertaken by CSIRO (including the results of the November 2018 pre-season survey), consultation with the TRL Resource Assessment Group and TRL Working Group and having regard to Australia's obligations under the Torres Strait Treaty.

*Moon-Tide Hookah Closures*

On 26 November 2018, the PZJA reaffirmed existing management controls currently applied to the TRL Fishery, to be implemented under the Instrument and licence conditions. This includes periodic closures to the use of hookah gear for three days either side of the full or new moon each month based on the largest difference between high and low waters.

In this letter, for the purpose of subsection 13(2) of the Instrument, I provide notice that the use, possession or control, on a boat, of hookah gear to take, process or carry TRL will not be permitted during the 2018/19 fishing season during the moon-tide hookah closure periods shown in the enclosed calendar (dated 28 November 2018). The first scheduled moon-tide hookah closure period starts on 17 February 2018.

These moon-tide hookah closures are in addition to the hookah closure period from 1 December and 31 January each fishing season. Free-diving, lamp fishing and traditional fishing are permitted during all hookah closure periods.

This letter only covers some of the key management arrangements that will apply this season. Licence holders should familiarise themselves with all management arrangements that apply in the TRL Fishery prior to the commencement of fishing. Further information can be found on the PZJA website at www.pzja.gov.au or by contacting AFMA.

Should you have any questions concerning the matters covered in this letter, please contact the AFMA Thursday Island office on 07 4069 1990 or FisheriesTI@afma.gov.au. If you would also like to receive future management updates by email or SMS please contact the AFMA Thursday Island office to update your contact details.

Yours sincerely

Anna Willock
Acting Chief Executive Officer

**Attachments**

- A Guide to the *Torres Strait Fisheries (Quotas for Tropical Rock Lobster (Kaiar)) Management Plan 2018*
- B Explanatory statement for the *Torres Strait Fisheries (Quotas for Tropical Rock Lobster (Kaiar)) Management Plan 2018*
- C *Torres Strait Fisheries (Quotas for Tropical Rock Lobster (Kaiar)) Management Plan 2018*
- D Explanatory statement for the *Torres Strait Fisheries Amendment (Tropical Rock Lobster) Management Instrument 2018*
- E *Torres Strait Fisheries Amendment (Tropical Rock Lobster) Management Instrument 2018*
- F Moon-tide hookah closure calendar for the 2018/19 fishing season (dated 28 November 2018)

## Torres Strait Tropical Rock Lobster Fishery Moon-Tide Hookah Closures for the 2018/19 Fishing Season* (as at 28 November 2018)

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Dec-18** | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon |
| | 1 | 2 | 3 | 4 | 5 | 6 | ● | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| **Jan-19** | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu |
| | 1 | 2 | 3 | 4 | 5 | ● | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| **Feb-19** | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | | | |
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| **Mar-19** | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun |
| | 1 | 2 | 3 | 4 | 5 | 6 | ● | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| **Apr-19** | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | |
| | 1 | 2 | 3 | 4 | ● | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | |
| **May-19** | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri |
| | 1 | 2 | 3 | 4 | ● | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| **Jun-19** | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | |
| | 1 | 2 | ● | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | |
| **Jul-19** | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed |
| | 1 | 2 | ● | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 |
| **Aug-19** | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat |
| | ● | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | ● | 31 |
| **Sep-19** | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | ● | 30 | |
| **Oct-19** | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | ● | 29 | 30 | 31 |
| **Nov-19** | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | Sun | Mon | Tue | Wed | Thu | Fri | Sat | |
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | ● | 27 | 28 | 29 | 30 | |

* The 2018/19 fishing season runs from 1 December 2018 through to 30 September 2019

**KEY**

● **New moon**

○ **Full moon**

**Fishery closed**

**Hookah closure (use of hookah gear not permitted)**

**Moon-tide hookah closure (use of hookah gear not permitted)**

Australian Government | Australian Institute of Marine Science | AIMS DATA CENTRE

# GBR - Coral Reef Temperature Dashboard

View as Map

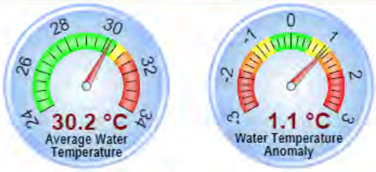
This site shows current water temperatures for selected reefs along the Great Barrier Reef using real time data from the AIMS and IMOS stations. The data is displayed in the context of the historical climatological record (how much warmer or cooler it is than the historical climatology) and how current temperatures relate to known empirical coral bleaching thresholds.

## Thursday Island

**Zone: Reef-Slope** **Sensor Depth: 4m**

Last Data: 29-Nov-18

**Current Status**




Temperature Status:

***Slightly Warmer than Normal***

Bleaching Status:

***Low Risk of Bleaching***

Explore

## Lizard Island

**Zone: Lagoon** **Sensor Depth: 8m**

Last Data: 29-Nov-18

**Current Status**


Temperature Status:

***Normal for this time of Year***

Bleaching Status:

***No Current Risk of Bleaching***

Explore

## Agincourt Reef

**Zone: Back-Reef** **Sensor Depth: 12m**

Last Data: 29-Nov-18

**Current Status**


Temperature Status:

***Slightly Warmer than Normal***

Bleaching Status:

***No Current Risk of Bleaching***

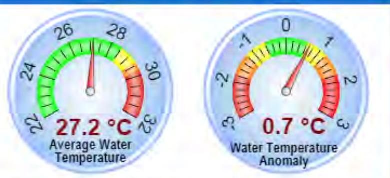
Explore

## Davies Reef

**Zone: Lagoon** **Sensor Depth: 4m**

Last Data: 29-Nov-18

**Current Status**




Temperature Status:

***Slightly Warmer than Normal***

Bleaching Status:

***No Current Risk of Bleaching***

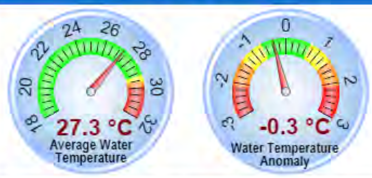
Explore

## Myrmidon Reef

**Zone: Slope** **Sensor Depth: 5m**

Last Data: 29-Nov-18

**Current Status**




Temperature Status:

***Normal for this time of Year***

Bleaching Status:

***No Current Risk of Bleaching***

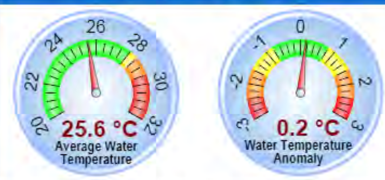
Explore

## Heron Island

**Zone: Lagoon** **Sensor Depth: 2m**

Last Data: 29-Nov-18

**Current Status**




Temperature Status:

***Normal for this time of Year***

Bleaching Status:

***No Current Risk of Bleaching***

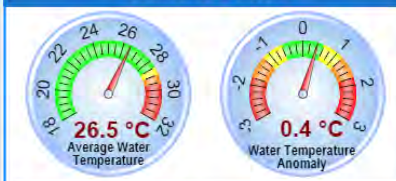
Explore

## Square Rocks

**Zone: Slope** **Sensor Depth: 3m**

Last Data: 29-Nov-18

**Current Status**




Temperature Status:

***Normal for this time of Year***

Bleaching Status:

***No Current Risk of Bleaching***

Explore

Australian Government | Australian Institute of Marine Science

# Coral Reef Temperature Dash-Board

AIMS DATA CENTRE

Back to Dashboard

## Thursday Island

### Bleaching Risk


| | |
|---|---|
| Current Avg. Water Temp: | 29.1 °C |
| Bleaching Warning Temp: | 31.0 °C |
| Bleaching Alert Temp: | 31.4 °C |

Bleaching Status:
***Low Risk of Bleaching***

### Thermal Anomaly


| | |
|---|---|
| Current Avg. Water Temp: | 30.2 °C |
| Historical Avg. Water Temp: | 29.1 °C |
| Temp Differential: | 1.1 °C |

Thermal Status:
***Slightly Warmer than Normal***

### Data Source

| | |
|---|---|
| Reef Name: | **Thursday Island** |
| Reef Zone: | **Reef Slope** |
| Sensor Depth: | **4.0m** |
| Region: | **Torres Strait** |
| Last Data: | **29-Nov-18** |
| Data Source: | **AIMS / TSRA Weather Station** |
| Climatology Range: | **May 1998 to Sept.2013** |

Metadata

Download Climatology

### Current Water Temperature versus historical Climatology

Current daily average water temperature (red line) plotted against the long term climatology (purple line) with the two Standard Deviation (SD) (blue and green lines) and the three Standard Deviation limits (dotted blue and green lines) shown. Temperatures are considered to be 'normal' if they lie between the +/- 2 SD lines, temperatures outside the +/- 3 SD limits are statistically extreme events.


### Day and Night Water Temperature Anomaly

Difference between the measured water temperature and the long term average, red lines are for daily averages, blue lines for night time (8pm-6am) data.

| | |
|---|---|
| **TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG)** | **MEETING 25**<br>**11-12 December 2018** |
| **UPDATES FROM MEMBERS**<br>**PNG National Fisheries Authority** | **Agenda Item 2.4**<br>**For Information** |

**RECOMMENDATIONS**

1. That the RAG **NOTE** the update to be provided by the PNG National Fisheries Authority (NFA).

**BACKGROUND**

2. A verbal report will be provided under this item.

| TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG) | MEETING 25<br>11-12 December 2018 |
| --- | --- |
| **UPDATES FROM MEMBERS**<br>**Native Title** | **Agenda Item 2.5**<br>**For Information** |

**RECOMMENDATIONS**

1. That the RAG **NOTE** any updates on Native Title matters from members, including representatives of Malu Lamar (Torres Strait Islanders) Corporation RNTBC (Malu Lamar).

**BACKGROUND**

2. On 7 August 2013 the High Court of Australia confirmed coexisting Native Title rights, including commercial fishing, in the claimed area (covering most of the Torres Strait Protected Zone). This decision gives judicial authority for Traditional Owners to access and take the resources of the sea for all purposes. Native Title rights in relation to commercial fishing must be exercisable in accordance with the *Torres Strait Fisheries Act 1984*.
3. Traditional Owners and Native Title representative bodies have an important role in managing Torres Strait fisheries. It is important therefore that the RAG keep informed on any relevant Native Title issues arising.
4. AFMA has extended an invitation to Malu Lamar to attend this meeting as an observer and is investigating longer term arrangements for representation in consultation with PZJA agencies.

| TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG) | MEETING 25<br>11-12 December 2018 |
|---|---|
| PRELIMINARY RESULTS OF THE NOVEMBER 2018 PRE-SEASON SURVEY | Agenda Item 3<br>For Discussion and Advice |

**RECOMMENDATIONS**

1. That the RAG **DISCUSS** and **PROVIDE ADVICE** on the preliminary results of the November 2018 pre-season survey (**Attachment 3a**), to be presented by CSIRO.

**KEY ISSUES**

*November 2018 pre-season survey*

2. CSIRO conducted the annual pre-season survey from 11-23 November 2018. A total of 80 sites were surveyed.
3. The pre-season survey data is a key data input for the integrated stock assessment and proposed empirical harvest control rule (HCR).
4. The preliminary results of the November 2018 pre-season survey will be presented by CSIRO at the RAG meeting. A summary report is provided at **Attachment 3a**.
5. The RAG is being asked to review the analysis and where relevant provide advice on the findings and/or need for further analysis.

*2018 mid-year survey*

6. The results of the 2018 mid-year survey were considered at TRLRAG24 on 18-19 October 2018:
    a. Plagányi E et al. 2018. Torres Strait TRL 2018 Midyear Survey Summary Report (**Attachment 3b**);
    b. Upston J et al. 2018. Torres Strait Tropical Rock Lobster Mid- and Pre-Season Surveys – Summary of observed and modelled size (tail width) distributions (**Attachment 3c**).
7. TRLRAG24 noted:
    a. 2+ index of abundance - the 2+ abundance index from the 2018 mid-year survey is significantly lower than the previous eight mid-year survey indices and is the second lowest value on record. The 2018 index is 26% of the average survey indices over the period 1989-2004. The 2018 index falls within the confidence limits associated with the stock assessment model prediction, and is slightly lower than predicted.
    b. Additional 5 sites – the 2018 index for the Mabuiag stratum decreased slightly when adding the additional 5 sites. This could be partly because the lobsters were very spatially concentrated in this stratum and the survey has underestimated overall abundance because it is designed to provide a larger scale representative index. Alternatively, this suggests that the earlier hotspot concentrations of lobsters in this stratum have now been fished and the index is reflecting a lower abundance following the fishing pressure that has been exerted in this area. Industry members advised that the majority of hotspot sites had been harvested before being surveyed.
    c. 1+ index of abundance - the 1+ recruiting abundance index is slightly higher than the upper 95% limit associated with the model prediction, and is seen to be at approximately the average historical value, suggesting that the 2018/19 fishing season will be improved relative to the 2017/18 fishing season.

d. Age class – there was an observed anomaly in the age class data where a significant proportion of the sampled lobsters fell between the average 1+ and 2+ age class ranges (i.e. meaning they were either larger 1+ lobsters or smaller 2+ lobsters). The RAG discussed a range of known factors that affects the growth of lobsters, including density dependence, water temperature, habitat and food availability. On the basis that water temperatures have been higher in more recent years, food availability has been high in the areas surveyed (e.g. good shell beds) and densities of lobsters have been lower, the best hypothesis to fit to this information is these lobsters are faster growing 1+ lobsters.

*CPUE analyses*

8. Updated catch and catch per unit effort (CPUE) data analyses for the TRL Fishery for the 2017/18 fishing season were considered at TRLRAG24 on 18-19 October 2018:

   a. Campbell R et al. 2018. Torres Strait Rock Lobster Fishery – Summary of the Catch and Effort Data pertaining to the 2018 Fishing Season (Dec-17 to Jul-18) (**Attachment 3d**);

   b. Campbell R et al. 2018. Use of TVH Logbook Data to construct an Annual Abundance Index for Torres Strait Rock Lobster – 2018 Update (**Attachment 3e**);

   c. Campbell R et al. 2018. Use of TIB Docket-Book Data to construct an Annual Abundance Index for Torres Strait Rock Lobster – 2018 Update (**Attachment 3f**);

9. TRLRAG24 noted that the standardised CPUE index for both the TIB and TVH sectors indicates a below average season in 2017/18 but not much below and within normal range compared across previous seasons. When comparing TIB and TVH indexes, the TVH index shows more inter-annual variability, but both sectors tend to be close to each other. Further details on discussions are provided in the meeting record at **Attachment 1.4a** to these meeting papers.

10. TRLRAG24 also noted the following analysis from Dr Éva Plagányi, CSIRO scientific member, comparing CPUE analyses against results for the 2017 pre-season and 2018 mid-year surveys:

    a. Estimating stock abundance using surveys versus CPUE – surveys do not target areas (i.e. they are randomly stratified) whereas fishers do target and they generally become more efficient over time in doing so. This can lead to a hyper-stability effect which occurs in stocks that aggregate and/or where there are increases in fishing power (effort creep) through time. This means industry can maintain high CPUE even when a stock is declining. If these factors are not taken into account in CPUE analyses, then the CPUE may not provide a reliable index of abundance. Surveys are specifically designed to give a more reliable index of abundance due to their randomly stratified nature and broader coverage of a Fishery area. Survey abundance indices will never exactly match industry CPUE trends: some years it will over-estimate and some years it will under-estimate, but on average there is a strong correlation between survey and CPUE data (i.e. the trend is similar).

    b. Relationship between CPUE and biomass in the Fishery – past modelling for the Fishery has shown that a non-linear regression line best fits the CPUE and mid-year 2+ data. This suggests that as stock abundance declines, CPUE is higher than what would be expected if there was a linear relationship or even accounting for hyper-stability. As a result of these past analyses, a hyper-stable relationship is assumed in the model (i.e. at low abundance, CPUE will be higher than true abundance). This assumption will be made clearer in future analyses. A further consideration is that if aggregation behaviour or fishing power changes from year-to-year, then the hyper-stable relationship will also change year-to-year, and may be able to explain some anomalous years. In summary, there is a hyper-stable relationship between CPUE and biomass in the Fishery, the stock in 2017/18 season was low and for various reasons outlined above, the CPUE data did not reflect this clearly. More accurate spatial and effort data would better inform CPUE analyses.

**BACKGROUND**

*2018 mid-year survey*

11. The TRL Fishery 2017/18 fishing season was managed in line with a historically low recommended biological catch (RBC). Historically, existing management arrangements for the TRL Fishery have been largely sufficient to keep catch levels below the Australian catch share of the RBC without the need for additional management controls. However, during the 2017/18 fishing season, catches were tracking to reach the Australian catch share of the RBC prior to the end of the season on 30 September 2018.

12. In response, changes were made to management arrangements within the fishing season for the purpose of prolonging the opportunity for the TIB sector to fish for the duration of the season and ensure the Australian catch share of the RBC was not exceeded. These changes were largely in the form of input controls (e.g. restrictions on the use of hookah gear) which had impacts on both fishers and the fishery-dependant data available to support future stock assessments.

13. In light of this, a TRLRAG meeting was held on 15 May 2018 (TRLRAG23), to consider these impacts and survey options to support future stock assessments and management of the TRL Fishery.

14. TRLRAG23 recommended that a mid-season survey be conducted as soon as practically possible, to be facilitated by industry and PZJA agencies, for the purposes of:

    a. providing further data on the abundance and spatial distribution of all age classes in the current season to input to the 2018/19 stock assessment, noting that CPUE data for the current season is now biased by management changes and may be unusable should the Fishery close early this season;

    b. providing further data to validate the 0+ and 1+ indexes of abundance from the November 2017 pre-season survey, noting the 0+ index may not have been reliably estimated from the November 2017 pre-season survey and the model was unable to satisfactorily fit this index;

    c. providing an 2+ index of abundance to more accurately inform on stock status and for comparison with CPUE data;

    d. provide a preliminary prediction of the expected 1+ lobster recruitment for the 2018/19 season (0+ lobsters in November 2017 pre-season survey) to provide forewarning on the likelihood of another low RBC for the 2018/19 season.

15. The survey was to consist of 77 pre-determined sites expressly selected to provide for comparison with previous mid-season surveys. The RAG further recommended that CSIRO work with industry to ensure areas fished in the current season are adequately represented in the sites sampled in the mid-season and future pre-season surveys.

16. A mid-year survey was conducted between 28 June and 9 July 2018. A total of 78 sites were surveyed by divers and each site was re-located accurately using portable GPS. 73 sites corresponded to the November 2017 pre-season survey, whereas 5 additional sites that were surveyed corresponded to the hotspot area fishers have focussed on during 2018. The selection of the 5 additional sites was circulated to RAG members and fishers for comment prior to the survey with agreement from those that responded that these sites were representative of the hotspot area for the 2018 season.

**Torres Strait TRL 2018 Pre-season Population Survey Summary**

*Mark Tonks, Nicole Murphy, Kinam Salee, Steven Edgar, Rob Campbell, Judy Upston, Éva Plagányi*

CSIRO Oceans and Atmosphere

Summary Report for Tropical Rock Lobster Resource Assessment Group - December 2018

## INTRODUCTION

The 2018 Tropical Rock Lobster (TRL) Pre-season Population Survey was conducted between $11^{th}$ and $23^{rd}$ November. The mothership “Wild Blue” (Rob Benn Holdings) supported the CSIRO TRL Dive Team (Mark Tonks, Nicole Murphy, Kinam Salee, Steven Edgar) in completing 82 survey sites (Figure 1). As a result of reported increases in TRL catches from the north-western Torres Strait at the commencement of the 2018 season, 5 additional sites were added (after consultation with stakeholders) to the July 2018 mid-year and November 2018 pre-season surveys to investigate lobster distribution.

Conditions during the 12 day survey varied with winds ranging between 15-25 knots for the first week and dropping to 5-10 knots for a majority of the second week. Visibility averaged between 2.5-3m with neap tidal flows allowing for a good visual census and collection of TRL.

## METHOD

The CSIRO TRL Dive Team used the standard $2000m^2$ belt transect method (2 divers per site each scanning 2m by 500m) with transect distance measured using a Chainman® device. At the completion of each transect divers recorded:

- The number of lobsters caught per age-class;
- The number and age-class of those observed but not caught;
- Depth;
- Visibility;
- Distance and direction swum from site co-ordinate.

In addition, species of interest (i.e. pearl oyster (*Pinctada maxima*), crown of thorns starfish and holothurian species) were counted and the habitat characterised.

Caught lobsters were measured (tail width, TW) to provide fishery-independent size-frequency data.

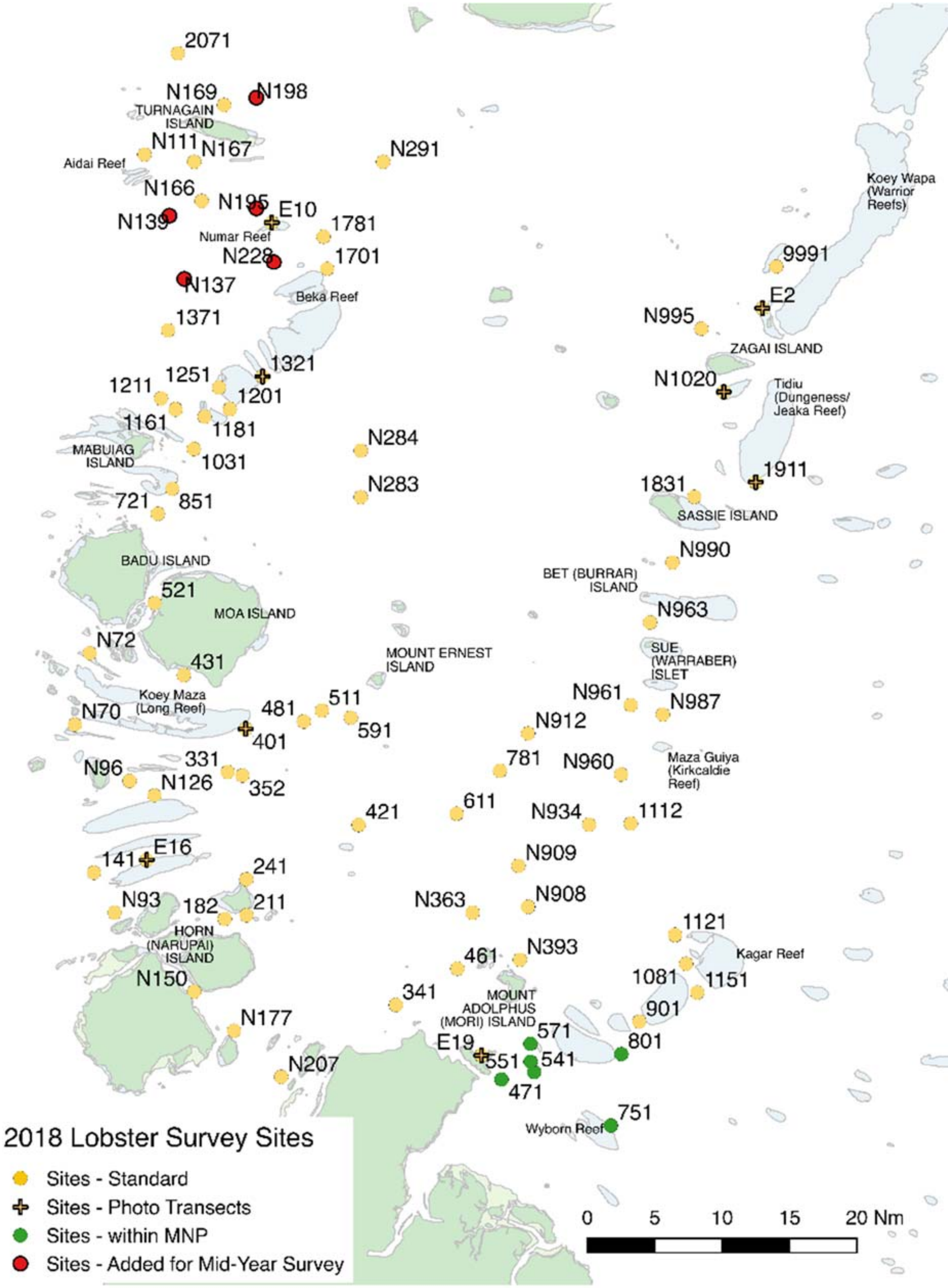



**Figure 1** Map of western Torres Strait showing sites surveyed during the 2018 TRL Pre-season Population Survey. The 5 additional sites surveyed are indicated in red.

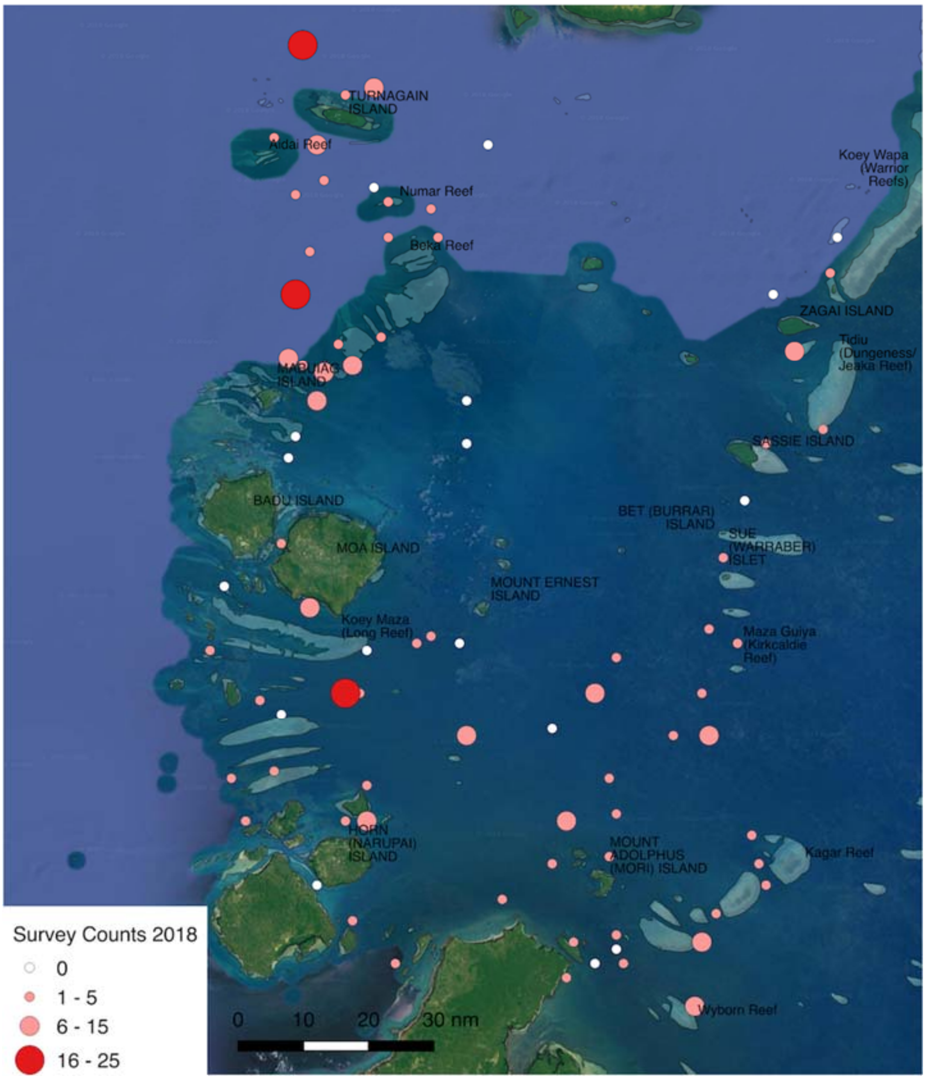
**RESULTS**

In total, 306 TRL were observed and categorised into age classes. Of these, 171 were collected, measured (TW) and their sex determined. With respect to total numbers per age-class the following was observed:

- 0+ (66);
- 1+ (234);
- 2+ (6).

The number of (Age 0+) lobsters observed in 2018 (66) was considerably more than the 19 observed in the 2017 pre-season survey and was more similar to the numbers observed in 2015(82) and 2016 (89). Similarly, (Age 1+) lobsters numbers (234) were well up from 2017 (138) and 2016 (148). As expected, (Age 2+) lobsters were rarely observed, as the majority of fished lobsters have emigrated from Torres Strait during August/September to undertake the breeding migration.

**LOBSTER COUNTS PER SITE**



## *ABUNDANCE INDICES*

### Recruiting lobster (Age 1+)

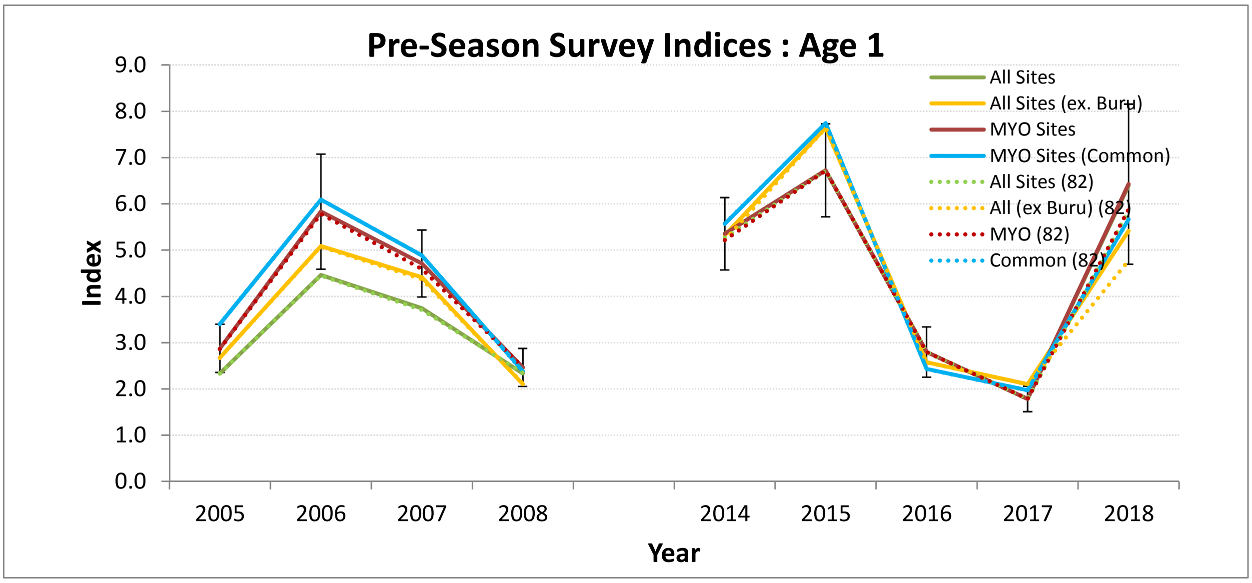



**Figure 2** Abundance indices of recruiting (1+) ornate rock lobsters (*Panulirus ornatus*) recorded during pre-season surveys in Torres Strait between 2005 and 2018. The data represents abundance indices for all sites as well as reduced series including Midyear-Only Sites (MYO). Error bars of MYO indices represent standard errors. (Note: pre-season surveys were not conducted during 2009-2013).

There are several abundance indices displayed in Figure 2. The index used in the stock assessment is the 'Mid Year Only' (MYO Sites) based on sampling of 77 transects. The 'MYO (82)' index includes the additional 5 sites (in the north-western part of the fishery), introduced in the 2018 Midyear survey to explore a potential lobster 'hotspot' based on commercial catches early in the 2018 fishing season. When comparing the two indices the 77-site index yields a slightly higher index for 2018 than the 82-site index. This is consistent with the finding during the Midyear survey.

The recruiting lobster (Age 1+) abundance index for 2018 pre-season survey highlights how variable recruitment to the fishery can be from year to year. In 2017, the lowest abundance index in the survey's history was recorded. In contrast, the 2018 index has increased significantly, recording the second highest index in the last 9 pre-season surveys. The 2018 index for recruiting lobster is approximately triple that of 2017. However, the standard error of the index reflects that the number of lobsters observed between sites was highly variable.

### Recently-settled lobster (0+)

Similar to the recruiting (Age 1+) lobster index, the recently-settled (Age 0+) lobster index increased from a record low in 2017 (Figure 3). The index reported in 2018 is lower than average, but is not significantly different from indices recorded in 2006, 2007, 2015 and 2016.

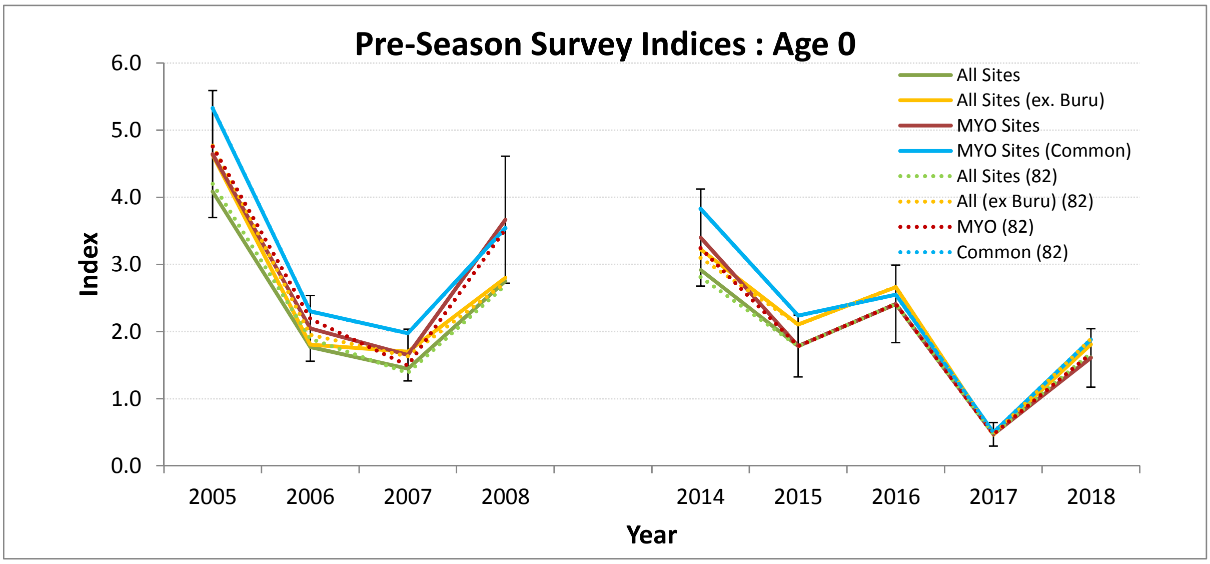



**Figure 3** Abundance indices of recently-settled (0+) ornate rock lobsters (*Panulirus ornatus*) recorded during pre-season surveys in Torres Strait between 2005 and 2018. The data represents abundance indices for all sites as well as a subset including Midyear-Only Sites (MYO). Error bars of MYO indices represent standard errors. (Note: pre-season surveys were not conducted during 2009-2013).

## DISTRIBUTION

### Recruiting lobster (Age 1+) distribution

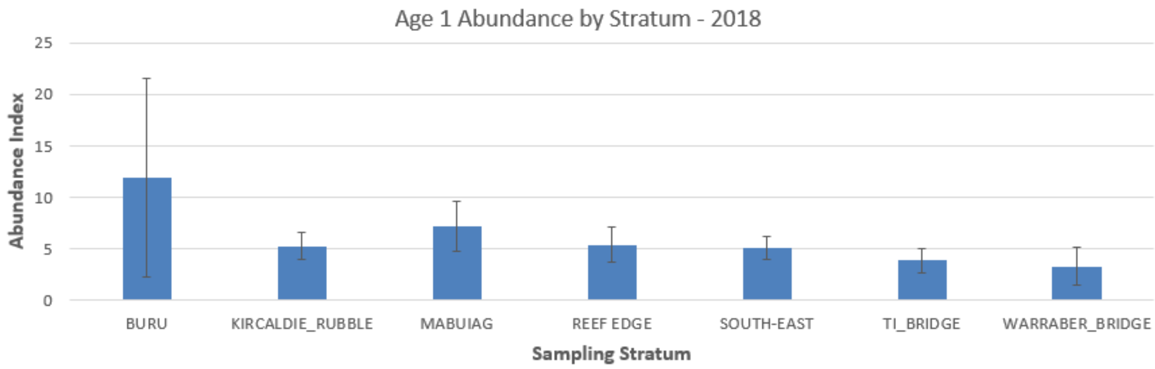



**Figure 4** Abundance indices of recruiting (1+) ornate rock lobsters (*Panulirus ornatus*) recorded in each sampling stratum for the 2018 pre-season survey.

The abundance index for the recruiting (Age 1+) lobster per stratum in 2018 suggests that recruitment to the fishery is widespread and consistent across most stratums. However, the north-western stratums, Buru and Mabuiag, have the highest recruitment, while Warraber Bridge had the lowest. The large standard error for Buru indicates that the number of lobster recorded at the sites within this region were highly variable.

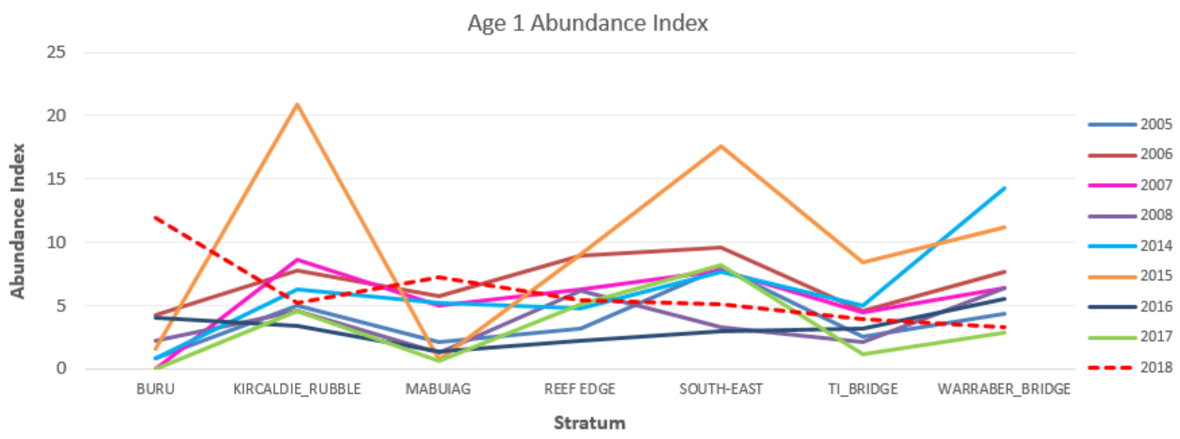



**Figure 5** Abundance indices of recruiting (1+) ornate rock lobsters (*Panulirus ornatus*) recorded in each sampling stratum during pre-season surveys in Torres Strait between 2005 and 2018. (Note: pre-season surveys were not conducted during 2009-2013).

A comparison of the recruiting (Age 1+) abundance indices by stratum for the last 9 surveys shows that Buru and Mabuiag have recorded their highest indices in 2018, with a considerable increase for Buru. The remaining stratums recorded average indices except for Warraber Bridge which indicated below average recruitment.

## Recently-settled lobster (Age 0+) distribution

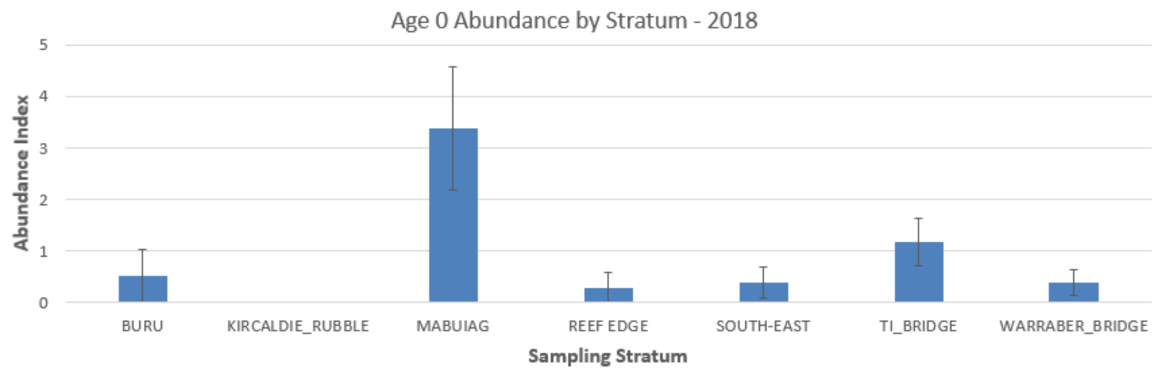



**Figure 6** Abundance indices of recently-settled (0+) ornate rock lobsters (*Panulirus ornatus*) recorded in each sampling stratum for the 2018 pre-season survey.

Historically, recently-settled (Age 0+) lobster are observed in higher numbers on the western side of the surveyed area. This is consistent with the 2018 results with the highest abundance indices recorded for Mabuiag, TI Bridge and Buru. Mabuiag recorded significantly higher abundances of recently-settled (Age 0+) lobster in comparison to the other strata.

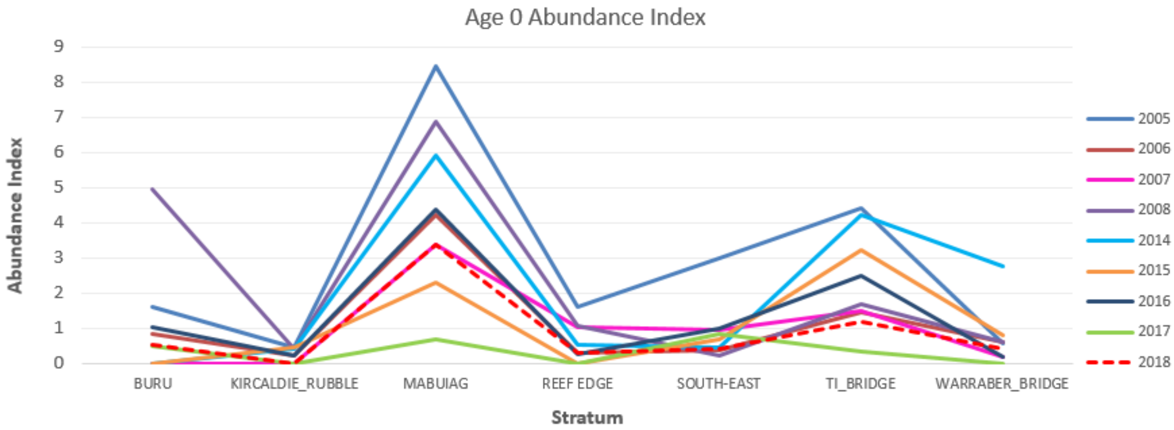



**Figure 7** Abundance indices of recruiting (0+) ornate rock lobsters (*Panulirus ornatus*) recorded in each sampling stratum during pre-season surveys in Torres Strait between 2005 and 2018 (Note: pre-season surveys were not conducted during 2009-2013).

In 2017, recently-settled (Age 0+) abundance indices were low across all stratums, resulting in the lowest overall index recorded in the last 9 surveys. Historically, the abundance indices were highest at Mabuiag and TI Bridge and lowest at Kircaldie, Reef Edge, South East and Warraber Bridge. The 2018 indices are consistent with these trends. However the indices observed at each stratum is lower than most other surveys.

## Length frequency

The size distribution of lobsters sampled during the 2018 pre-season survey was similar to previous surveys in that it was comprised mostly of (Age 1+) lobsters. Since 2014 the modal size of (Age 1+) lobsters had been generally decreasing, however the modal size in 2018 has increased and is similar to size data collected in 2005 (Figure 8).

The sex ratio for the 2018 recruiting age-class (1+) was almost exactly 1:1 which is to be expected .

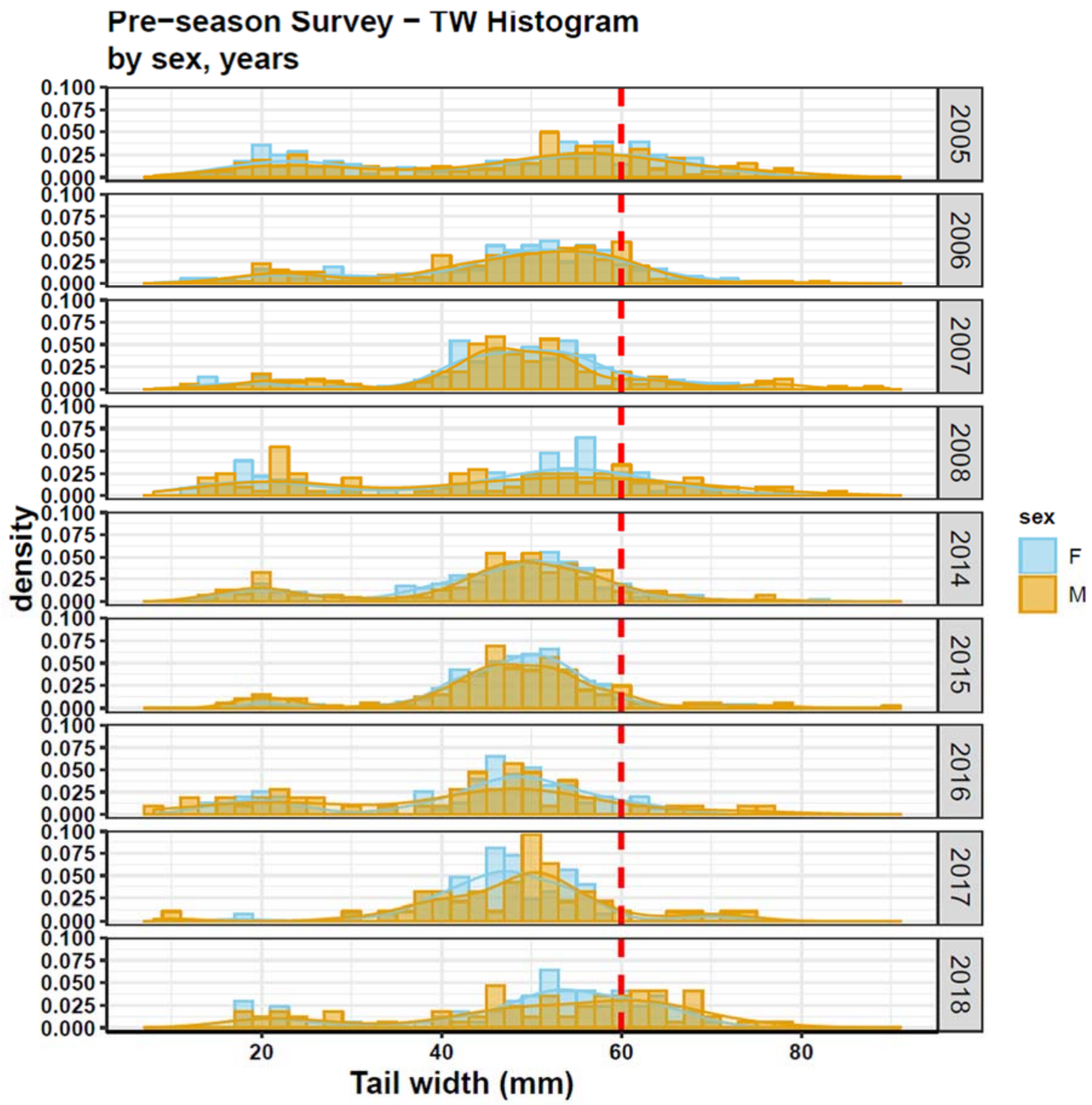



**Figure** 8 Length frequency distributions of lobster (*Panulirs ornatus*) sampled during pre-season population surveys in Torres Strait in 2005-2008, 2014-2018. The dotted line represents legal sixe (90mm CL ≈ 60 mm tail width).


## Acknowledgements

We wish to sincerely thank the master (Rob Benn) and crew (Ian Kingswood) of the Wild Blue for excellent assistance in all aspects of the pre-season dive survey in Torres Strait, and in logistic support prior to and after the field survey. We gratefully acknowledge funding support for the survey from AFMA and CSIRO.

# Torres Strait TRL 2018 Midyear Survey Summary Report

*Éva Plagányi, Mark Tonks, Robert Campbell, Nicole Murphy, Frank Coman, Kinam Salee, Judy Upston, Roy Deng*

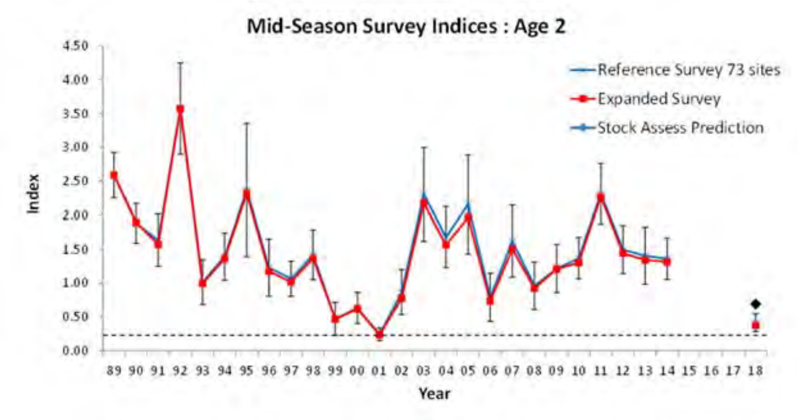
CSIRO Oceans and Atmosphere

## Abstract

The 2018 Midyear survey of the Torres Strait lobster population was conducted between 28th June - 9th July 2018 using the mothership Wild Blue (Gladstone) and CSIRO tender. The survey has shown convincingly that the original scientific results and recommendations hold, i.e. the observed 2018 2+ survey index is NOT significantly different to the stock assessment model-predicted value. The survey results therefore recommend no increase in this year's RBC based on the process agreed at the May 2018 TRLRAG: "*The RAG recommended a review of the RBC be undertaken if the results of the 2018 mid-season survey 2+ survey index falls outside the 95% confidence interval associated with the model forward prediction based on the November 2017 pre-season survey 1+ index, in relation to directly comparable sites (e.g. sites sampled in both surveys only).*" The survey result suggests that the 2+ stock abundance (being the cohort that will contribute to spawning) is lower than predicted based on forward projections (it's the 2nd lowest index after the 2001 minimum value), and hence that a low precautionary RBC is warranted.

The survey suggested that the incoming 1+ recruiting cohort is slightly above average and hence preliminarily suggests that next year will be a much better year. The 1+ index is higher than would have been predicted by the Preseason 0+ index. However previous analyses acknowledged that the 0+ index was negatively biased and the stock assessment model downweighted it based on the high associated standard deviation. This year's November 2018 Preseason survey will be able to corroborate the Midyear 1+ index, which is a key input for computing next year's RBC. Previous analyses showed that the relationship between recruiting (1+) lobster indices recorded from mid-year and pre-season surveys in the same years was highly significant ($R^2$=0.97), which isn't too surprising given that the surveys were conducted only four months apart (June and November).

The midyear survey index has provided a valuable basis for calibrating this year's CPUE, but we won't be able to start those analyses until we have the entire year's CPUE data analysed. The full report containing the detailed analyses of the survey data will be circulated before the next TRLRAG meeting.




Key summary figure showing July 2018 Midyear standardised survey index relative to historical values and compared with the stock assessment prediction (based on the 2017 Preseason survey).

## 1. Introduction

The May 2018 TRLRAG recommended the following: "*that a mid-season survey be conducted as soon as practically possible, to be facilitated by industry and PZJA agencies, for the purposes of:*

- *providing further data on the abundance and spatial distribution of all age classes in the current season to input to the 2018/19 stock assessment, noting that CPUE data for the current season is now biased by management changes and may be unusable should the Fishery close early this season;*
- *providing further data to validate the 0+ and 1+ indices of abundance from the November 2017 pre-season survey, noting the 0+ index may not have been reliably estimated from the November 2017 pre-season survey and the model was unable to satisfactorily fit this index;*
- *providing a 2+ index of abundance to more accurately inform on stock status and for comparison with CPUE data;*
- *provide a preliminary prediction of the expected 1+ lobster recruitment for the 2018/19 season (0+ lobsters in November 2017 pre-season survey) to provide forewarning on the likelihood of another low RBC for the 2018/19 season.*

*The survey will consist of 77 pre-determined sites expressly selected to provide for comparison with previous mid-season surveys.*

*The RAG further recommended that CSIRO work with industry to ensure areas fished in the current season are adequately represented in the sites sampled in the mid-season and future pre-season surveys*."

Annual fishery-independent monitoring of the Torres Strait ornate rock lobster *Panulirus ornatus* population has been carried out between 1989 and 2018. Midyear surveys were conducted for all years 1989-2014, with the 2018 survey extending this series. Pre-season surveys have been conducted for years 2005-2008 and 2014-2017. These surveys provide the only long-term information on the relative abundance of recruiting (1+) and fished (2+) lobsters, since there was no comprehensive monitoring of commercial catch and effort prior to 2003. The survey sites are distributed throughout the majority of the fished area to provide representative abundance estimates. The relative abundance indices and age composition data are used in the TRL fishery model for assessments of the status of the stock, and to inform management regulations.

The 2018 Midyear survey of the Torres Strait lobster population was conducted between 28$^{th}$ June - 9$^{th}$ July 2018 using the mothership *Wild Blue* (Gladstone) and CSIRO tender (Figure 1). A total of 78 sites were surveyed by divers and each site was re-located accurately using portable GPS. Seventy-three sites corresponded to the 2017 Preseason survey, whereas 5 additional sites that were surveyed corresponded to the hotspot area fishers have focussed on during 2018 (Figure 2). The selection of the 5 additional sites was circulated to TRL RAG members and fishers for comment prior to the survey with agreement from those that responded that these sites were representative of the hotspot area for the 2018 season. The four scientific divers involved in the survey ranged in experience with two divers having more than 10 surveys experience while the other two had completed 2 or 3 TRL surveys. The two dive teams were split based on experience with a less experienced diver coupled with a more experienced diver. Measured belt transects (500 m by 4 m) were employed as the primary sampling unit, as they were found to give the greatest precision (p=SE/Mean) of lobster abundance. Transect distance was measured, to the nearest metre using a Chainman® device. At the completion of each transect divers recorded: the number of lobsters caught, the number and age-class of those observed but not caught, depth, visibility, distance swum, numbers of pearl oyster (*Pinctada maxima*), crown of thorns starfish  and holothurian species observed, and percent covers of standard substratum and biota (including seagrass and algae species) categories. The sampled lobsters were measured (tail width in mm), sexed and moult staged to provide fishery-independent size-frequency data.

The only glitch was an early hydraulic pump breakdown on the vessel, but the experienced crew were very helpful and efficient and the boat was fast so the team caught up time. The weather and underwater conditions for the survey were generally good. There were some strong winds (20-25 knots) for the first 7-8 days, dropping to 15-20 knots over the last 3 days. The visibility was good, averaging 2.5-3m. The lowest recorded visibility was 1.5m.

As previously, diving operations were limited by a Marine Park Permit to take only 5 lobsters per site from 6 sites located within the Great Barrier Marine Park Zone in the SE region of the fishery. Restrictions included: collection of no more than 30 juvenile lobster (< 90mm carapace length) from the 6 sites per year and no more than 5 collected per site per year.

Figure 1. Vessels used for 2018 midyear survey: mothership Wild Blue and a 5m CSIRO naiad

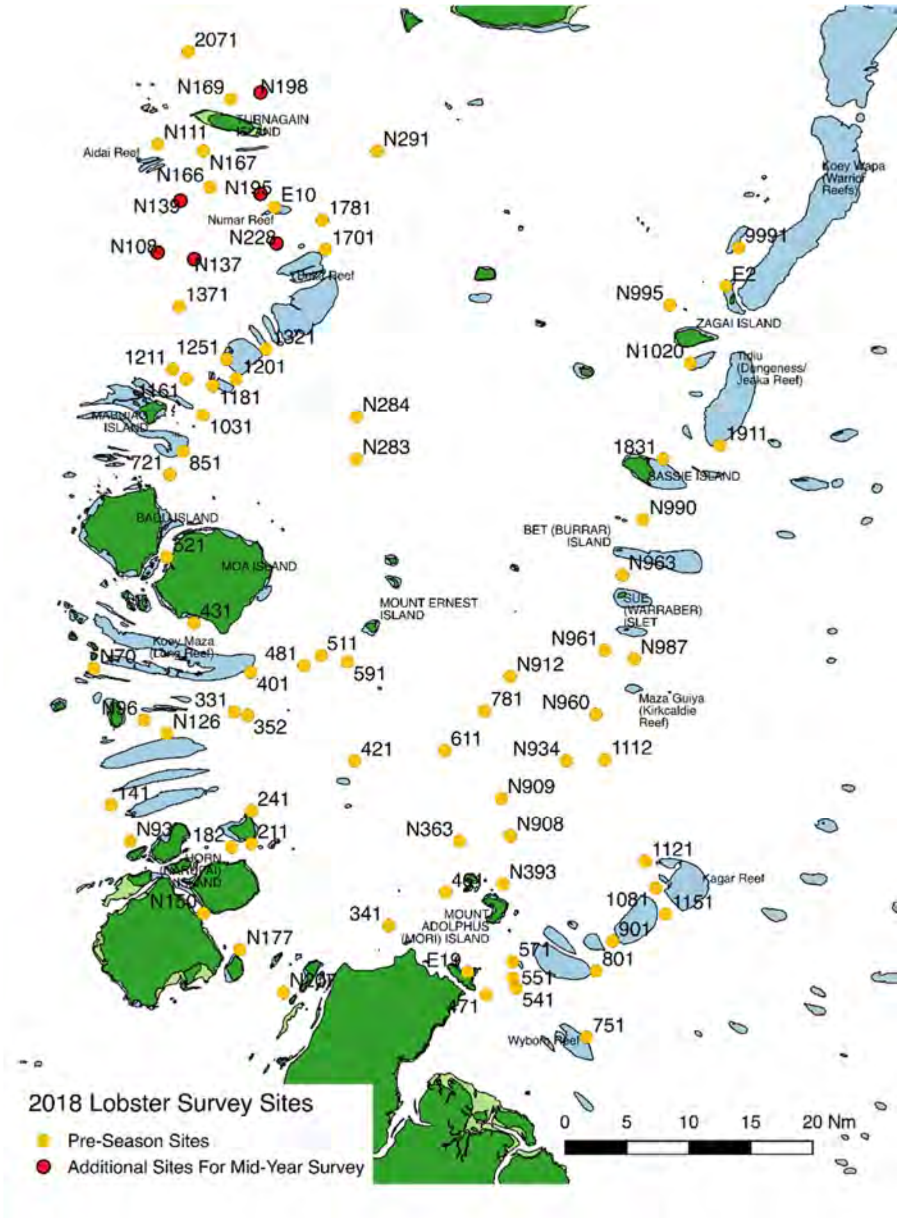



Figure 2. Map of western Torres Strait showing sites surveyed during the 2018 TRL midyear population survey. Sites marked in yellow are the same sites as surveyed in the 2017 Preseason survey whereas the red marks indicate additional sites added to the Midyear Survey.

***Fishing Effort***: Previous midyear surveys have been conducted during the fishing season. There was concern that the 2018 midyear survey might be positively biased due to reduced fishing effort this year as a result of a low RBC, plus concern that the fishery might close before the start of the survey if the RBC was reached, and because of a hookah ban implemented mid-season.

The 2017/18 total RBC is 299t. Following a recent agreement between Australia and PNG on the allocation of the 2017/18 recommended biological catch (RBC) for the Torres Strait Tropical Rock Lobster Fishery (TRL Fishery), there will be no cross endorsement and hence the final Australian catch share is 254.15 tonnes. This is an increase from 190.65 tonnes. The sustainable catch limit for the

Australian sector for the 2017/18 fishing season is thus 254.15 tonnes and the total reported catch as at 12 July 2018 was 228.12 tonnes, with 24 t taken from 1-12 July. Assuming that the PNG catch as at 12 July was 45t, this suggest the total catch up until the end of the midyear survey was approximately 273t.

Other fishery restrictions this year have included additional moon-tide closures and a hookah ban for a short time period. However, the use of hookah gear was again permitted from 2-9 July 2018, and hence it can be assumed that the total level of fishing effort preceding and during the time the midyear survey was conducted was not overly anomalous. However there are indications from the data and from anecdotal reports from fishers that the fishing effort has been fairly locally concentrated this year, and hence high fishing pressure in the Mabuiag stratum in particular could influence results.

## 2. Results

*TRL distribution and abundance*

The distribution of recruiting (1+) lobsters observed during the 2017 Preseason survey was compared with the 2+ lobster abundance (given they have grown into the next age class) during the 2018 Midyear survey (Fig. 3). Both survey indices suggested low abundance of the (1+) lobsters in November 2017 and the same cohort (2+) in June/ July 2018 across most strata. Buru stratum had one of the higher 2+ indices from the 2018 Midyear survey which contrasted with the very low 1+ abundance index observed for this stratum in the November 2017 preseason survey. The South East stratum which had an average 1+ index in November 2017, had a low Midyear 2+ index indicating the expected northward movement of lobsters as they grow and prepare for migration around September. In general, there were plenty of sites with empty dens where one might have expected 2+ animals if the abundance was high.

The 2018 recruiting class (1+) suggests a more even distribution of recruits than was the case last year (Fig. 3). The Midyear survey indicated that all strata had reasonable numbers of 1+ recruits however the north-western stratums (Buru and Mabuiag), and the South-East stratum had higher indices compared to the others.

*Annual indices of abundance for 1+ and 2+ lobster*

As the 2015, 2016 and 2017 pre-season surveys involved a reduced number of transects (77) from previous surveys (>130, e.g. 2014), a number of alternative methods have been used to calculate annual pre-season indices of abundance between 2005 and 2017. Previous analyses indicated that transitioning to smaller scale pre-season surveys would not interrupt the time series collected to date. Moreover, analyses were done to cross-check the reliability of using subsets of the survey data, such as selecting for analysis of the Preseason survey index, only those sites also common to the earlier Midyear surveys. As the Preseason survey becomes more extensive, more recent additions to the survey could be included in the standardised index. The 2018 Midyear survey used mostly the same reference sites (73) as per the 2017 Preseason survey but also included an additional 5 sites in the Mabuiag stratum where most fishery catches were being reported from. There were therefore 4 alternative methods (Table 1) used to analyse the 2018 Midyear survey index relative to previous years. The first involved using exactly the same method as was used to obtain the Reference Case Preseason 1+ index from the 2017 Preseason survey (using 68 common sites), being the series that was input to the stock assessment model. The second method involved using all 73 sites as used in the Preseason survey. The third method used all 78 sites, i.e. including the additional 5 sites. The fourth used only sites common to all years.

The 2018 midyear abundance index for 2+ lobsters is significantly lower than the previous 8 midyear survey indices and is the second lowest value on record (Fig. 4). The 2018 index is 26% of the average survey indices over the period 1989-2004 (Fig 4). The overall pattern of a low 2018 index is very similar across all methods examined.

The (1+) recruiting index is much more positive and is at approximately the average historical level, suggesting that the next fishing season will be improved relative to the current fishing season (Figure 4).

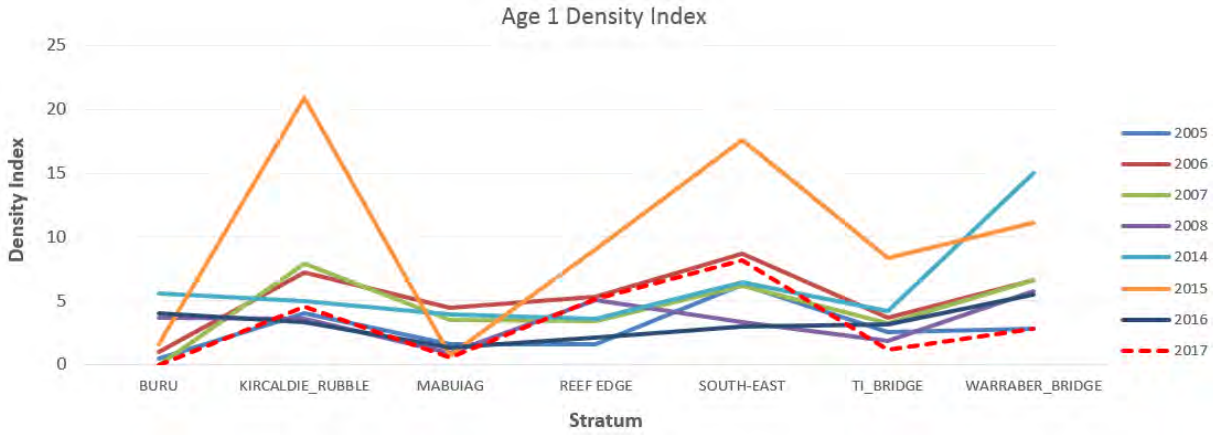
Figure 5 compares the standard errors (SE) of the alternative survey indices, highlighting the improvement (i.e. reduction in standard error) in the precision of surveys with substantially more sites (e.g. 34 vs 73 sites) but only a small change in precision associated with adding a few more sites. The 2018 coefficient of variation (SE/mean) for both the 2+ and 1+ indices was similar to the average of the historical series, supporting that the 2018 midyear survey was adequately precise.

Table 1. Description of the four options used to estimate ornate rock lobster (*Panulirus ornatus*) abundance indices from the 2018 Midyear population survey conducted in Torres Strait.

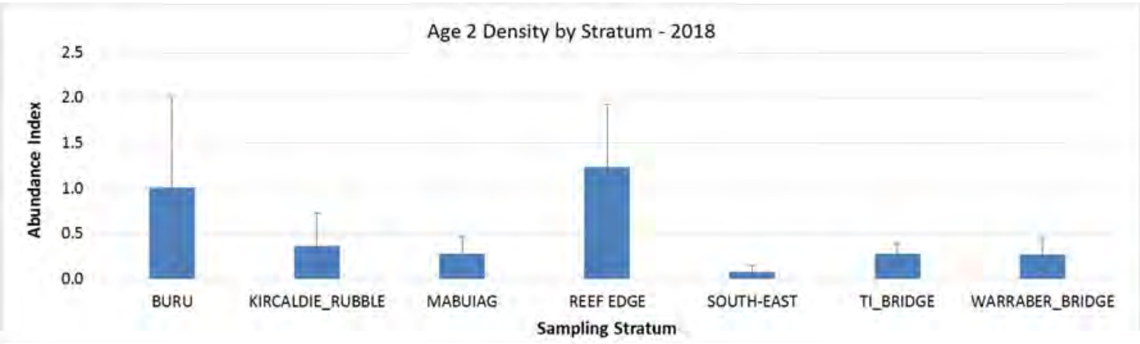
| **Midyr Index Option** | **Number of Transects in 2018** | **Total Number of Transects in series** | **Description** |
|---|---|---|---|
| 1. 73 Reference Sites | 73 | 73# | The 73 Reference Sites used in the 2018 survey |
| 2. Reference Index used in Stock Assessment Model | 68 | 73# | Historically selected reference sites : Sites common to those in the 2002 and 2006 surveys |
| 3. Expanded survey | 78 | 83 | Sites used in Option 2 plus the additional sites in the 2018 survey |
| 4. MID_YEAR ONLY SITES- common across all years | 34 | 34 | Sites common to surveys across all years |

# Of the 73 sites included in options 1 and 2 above, 68 sites are common to both options while 5 sites are particular to each option.

November 2017 Preseason Survey




July 2018 Midyear survey



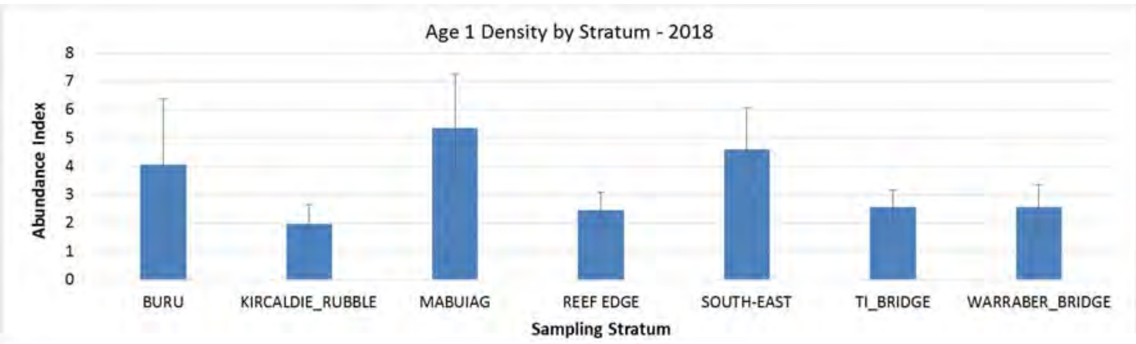
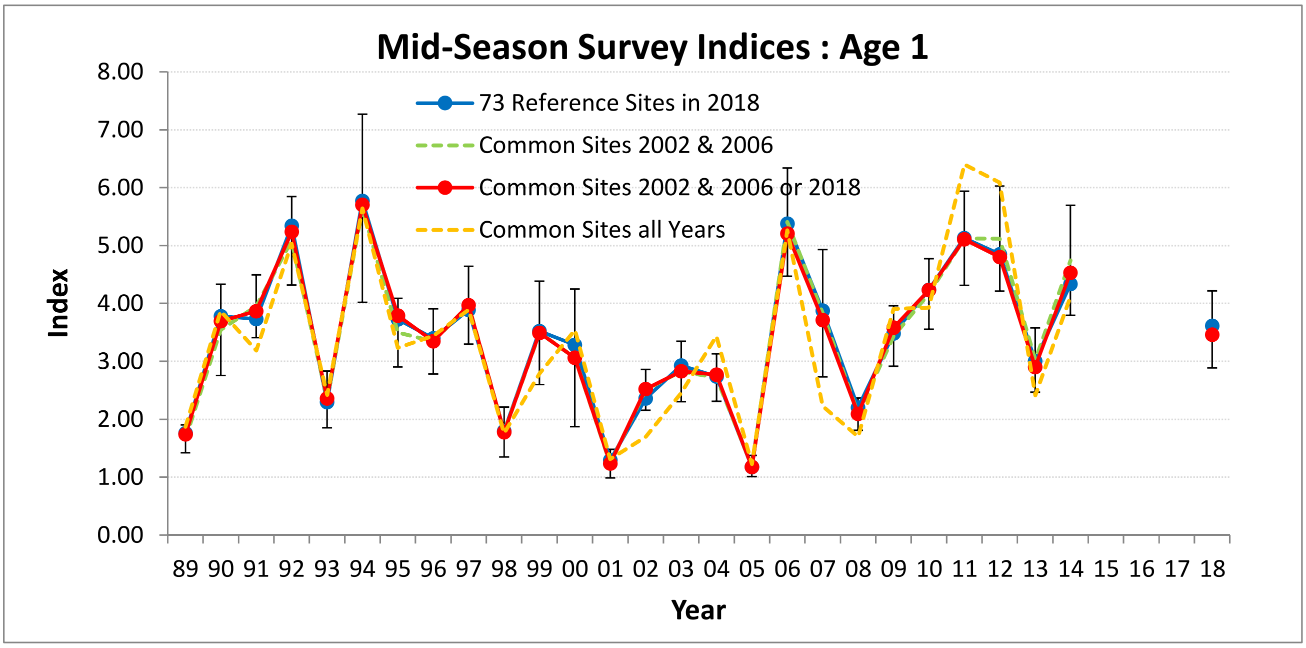




Figure 3. Comparative indices of abundance of recruiting (1+) ornate rock lobsters (*Panulirus ornatus*) recorded in each sampling stratum during pre-season surveys in Torres Strait between 2005 and 2017 (note surveys were not done during 2009-2013), compared with results (based on all 78 sites) obtained during the July 2018 Midyear survey



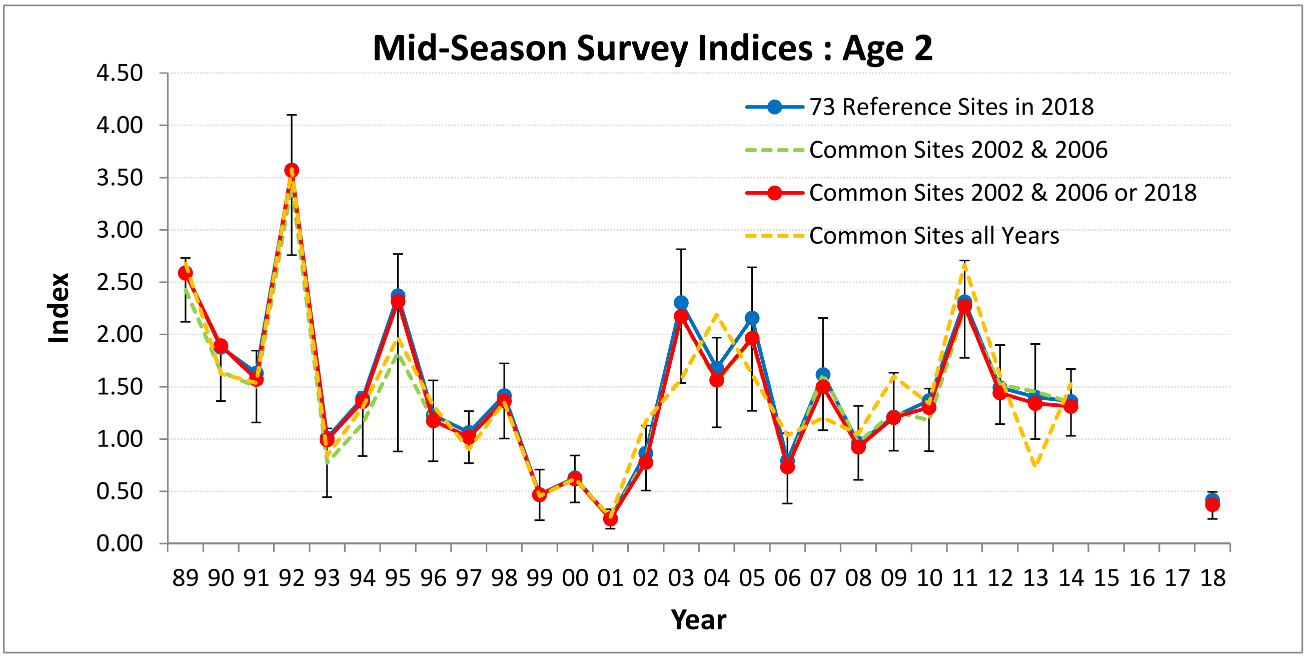
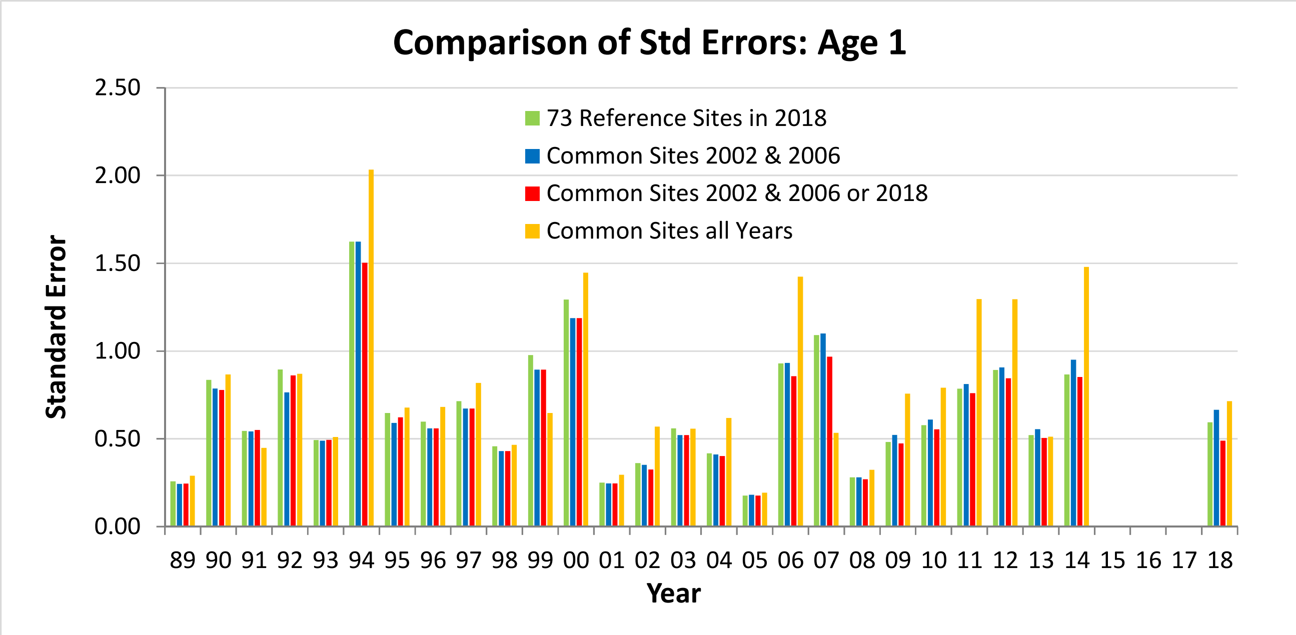




Figure 4. Four comparative indices of abundance of recruiting (1+) and fished (2+) ornate rock lobsters (*Panulirus ornatus*) recorded during midyear surveys in Torres Strait between 1989 and 2018 (note midyear surveys were not done during 2005-2017). Error bars of MYO indices represent standard errors.



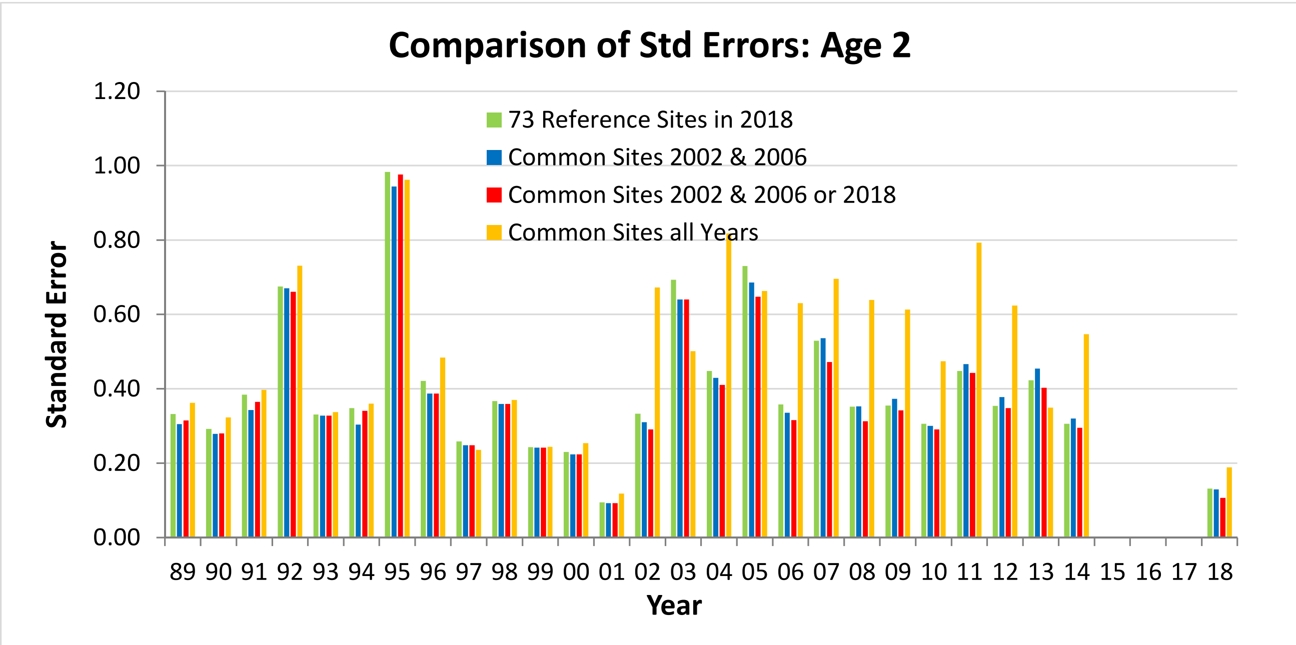




Figure 5. Comparative standard errors for four indices of abundance of recruiting (1+) and fished (2+) ornate rock lobsters (*Panulirus ornatus*) recorded during midyear surveys in Torres Strait between 1989 and 2018 (note midyear surveys were not done during 2005-2017).

***Evaluating Results relative to predictions based on the 2017 Preseason survey and Stock Assessment Model Predictions***

The TRLRAG May 2018 meeting noted the following with regard to at what point the mid-season survey may trigger a review of the RBC for the TRL Fishery: "*The AFMA member advised that there would need to be a significant variation between the results of the November 2017 pre-season survey and the 2018 mid-season survey to trigger a review. Such an "anomalous" result is considered unlikely at this point given indications from available data for the Fishery to date. The CSIRO scientific member supported this view and suggested an anomalous result be defined as a 2018 mid-season survey 2+ survey index that falls outside the 95% confidence interval associated with the model forward prediction based on the November 2017 pre-season survey 1+ index. This is given uncertainties in available data and the fact that a mid-season survey has not been conducted since 2014. The RAG noted that a 95% confidence interval sets a high bar, but agreed that this would be appropriate.*"

As shown in Table 2 and Figure 6, the midyear 2+ index falls within the confidence limits associated with the stock assessment model prediction, and is slightly lower than predicted. As per the agreed process for evaluating results, this therefore suggests that no increase in the RBC is warranted.

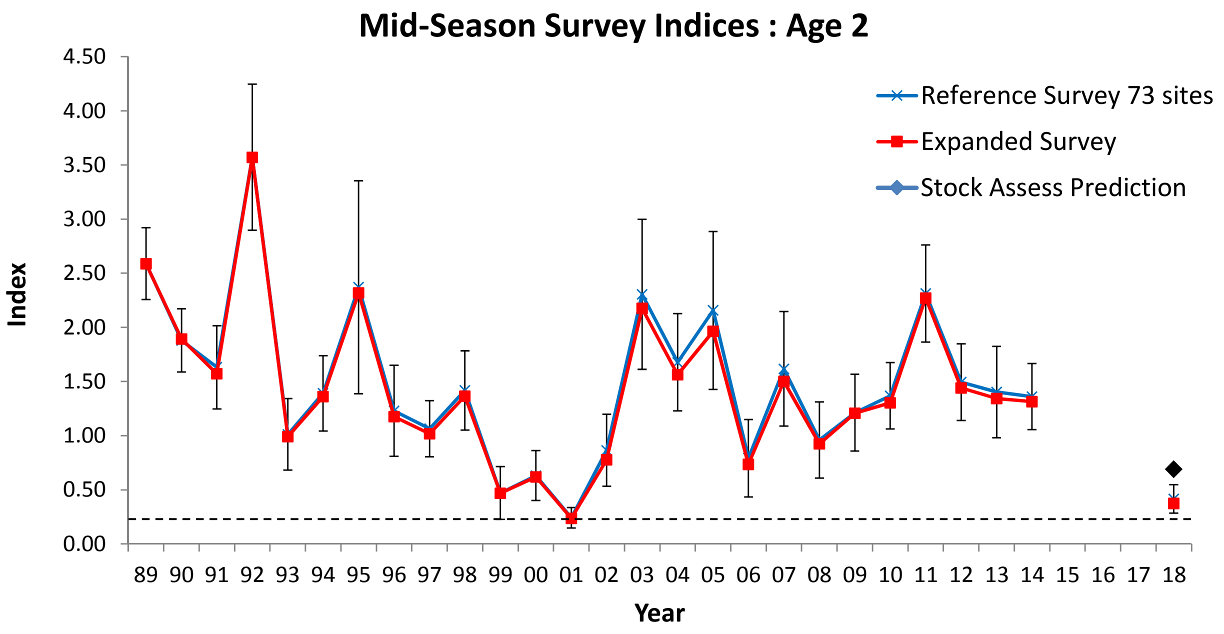
The midyear survey also provides an early indication of the recruiting (1+) age class, which is helpful given the 0+ index is considered unreliable. As evident from table 2 and Fig. 6, the 1+ index is slightly higher than the upper 95% limit associated with the model prediction, and is seen to be at approximately the average historical value, suggesting a more positive outlook for next year.

Table 2. Stock assessment model (Dec 2017 Reference Case version) prediction of 2018 Midyear survey expected relative numbers (i.e. equivalent to survey index) of 1+ and 2+, shown with lower and upper 75% and 95% confidence limits, compared with actual Observed values from 2018 Midyear survey.

| | **Observed** | Predicted Value | lower95% | upper95% | lower75% | upper75% |
|---|---|---|---|---|---|---|
| 1+ | **3.56** | 2.69 | 1.84 | 3.54 | 2.10 | 3.47 |
| 2+ | **0.37** | 0.69 | 0.34 | 1.04 | 0.44 | 0.93 |

*Comparison with additional sites added to the index*

The additional 5 sites were added to the Mabuiag stratum given information that the stock distribution has shifted this year and fishing has been concentrated in this stratum. It was therefore anticipated that the absence of these sites in the 2017 Preseason survey may have biased results negatively, and that the bias could be evaluated by comparing with results from an index including additional sites in the "hotspot" area. As shown in Fig. 8, a difference in the stratum-specific indices is therefore only expected for the Mabuiag stratum. However, in contrast to the expected results, the index for the Mabuiag stratum actually decreased slightly when adding the additional 5 sites. This could be partly because the lobsters are very spatially concentrated in this stratum and the survey has underestimated overall abundance because the survey is designed to provide a larger scale representative index. Alternatively, this suggests that the earlier "hotspot" concentrations of lobsters in this stratum have now been fished and the index is reflecting the fishing pressure that has been exerted in this area. In summary though, this suggests that there is no basis for concluding that lobster abundance is significantly higher than indicated by the survey and hence that the RBC should be increased.



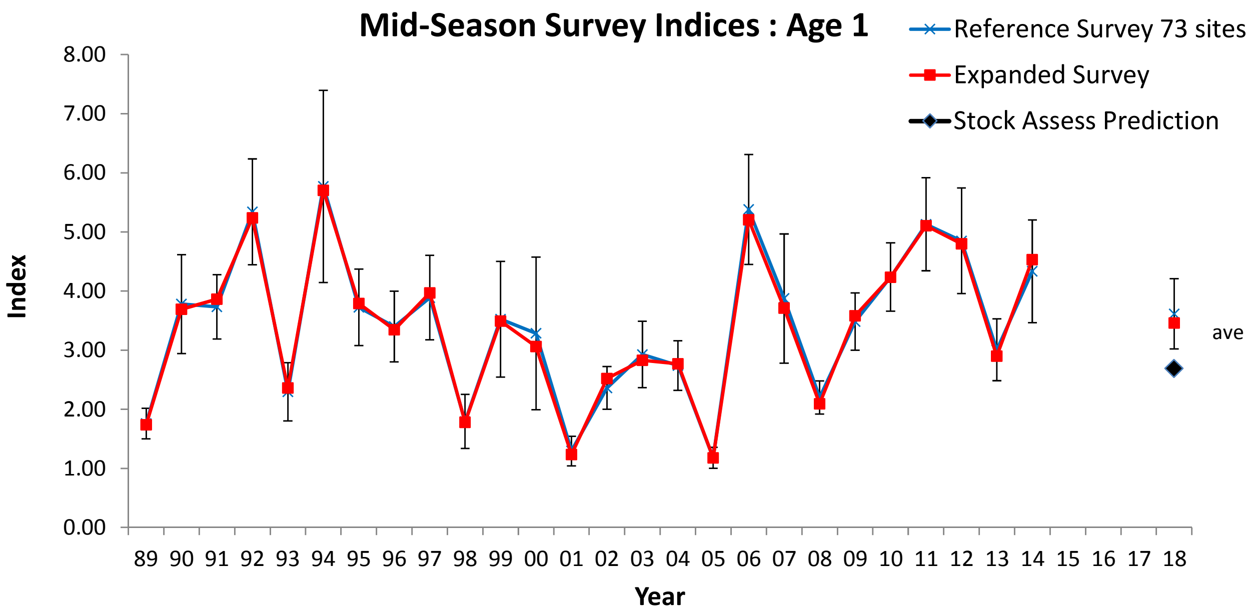
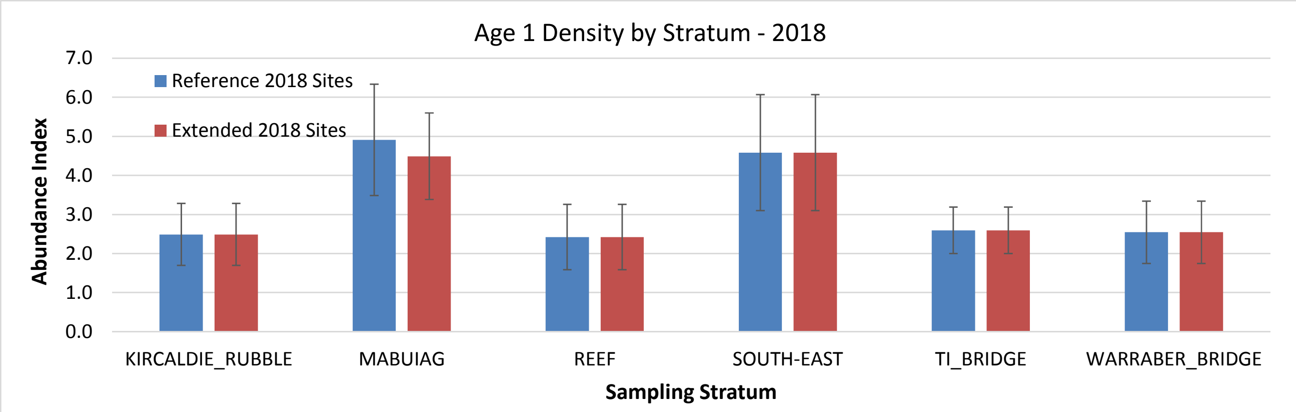




Figure 6. Comparison of the Reference and Expended Survey indices of abundance of recruiting (1+) and fished (2+) ornate rock lobsters (*Panulirus ornatus)* recorded during midyear surveys in Torres Strait between 1989 and 2018 (note midyear surveys were not done during 2005-2017), shown together with the stock assessment model-predicted values that were based on the model fitted to the Preseason 2017 survey data. Error bars represent standard errors.



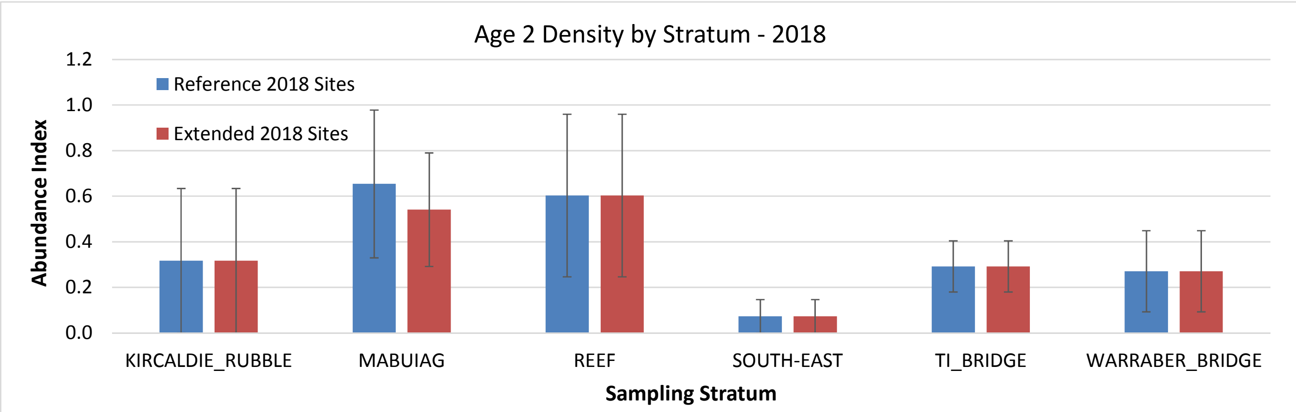




Figure 7. Comparison of 2018 Midyear survey results per stratum as shown.

The midyear survey index has provided a valuable basis for calibrating this year's CPUE, but we won't be able to start those analyses until we have the entire year's CPUE data analysed. The full report containing the detailed analyses of the survey data, including length frequency information, will be circulated before the next TRLRAG meeting.

## Acknowledgements

We wish to sincerely thank the master (Rob Benn) and crew (Joseph Harland) of the Wild Blue for excellent assistance in all aspects of the mid-year dive survey in Torres Strait, and in logistic support prior to and after the field survey. We also thank Tim Skewes for stepping in to assist with the diving and sharing his extensive experience from decades of involvement in TRL research. We are grateful to Darren Dennis for comments which helped improve the analyses. Finally we thank all TRL RAG members and observers for their constructive inputs. We gratefully acknowledge funding support for the survey from AFMA and CSIRO.

# Torres Strait Tropical Rock Lobster Mid- and Pre-season surveys – Summary of observed and modelled size (tail width) distributions.

Judy Upston, Éva Plagányi, Mark Tonks, Tim Skewes, Kinam Salee, Frank Coman, Nicole Murphy, Rob Campbell, Mick Haywood, Roy Deng, Trevor Hutton

With thanks to Darren Dennis for valuable contributions to the TRL research

CSIRO Oceans and Atmosphere, Australia

Paper for TRL RAG, October 2018

## Summary

This paper comprises a summary of observed and modelled size (tail width) distributions for Torres Strait tropical rock lobsters based on observations from independent research surveys during the Mid-Season (June/ July) and Pre-season (November/ December), with emphasis on 2018 and recent survey years. The paper provides a reference set of summary statistics and plots to support discussion by the TRL Research Advisory Group, as necessary.

## Acknowledgements

Thank you to Rob Benn and Joseph Harland on the Wild Blue vessel for their contributions to successful field operations for the 2018 mid-year survey in Torres Strait. We also thank TRL RAG for their valuable discussions. Funding support for the 2018 survey was provided by AFMA and CSIRO.

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Figure D2. Diagnostic plot. Mid-Season 2018 Histogram (density distribution) of TS rock lobster TW by sex and zones.
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Figure A2. Mid-Season Survey – Histogram (counts) of TS rock lobster TW by sex, years.
Figure A3. Pre- and Mid-Season Surveys – Histogram (counts) of TS rock lobster TW by sex, years surveyed (since 2013).
Figure A4. Diagnostic plot. Mid-Season Survey - Histogram (counts) of TS rock lobster tail width (TW) by sex and areas (North and South), 2018 and recent years surveyed.
Figure A5. Diagnostic plot. Mid-Season Survey 2018 - Histogram (counts) of TS rock lobster tail width (TW) by sex and zone). Zones: 1=North West, 2=South West, 3=Central, 4=South East.

## 1. Tables and Figures

**Table 1. Number of TS rock lobsters (n_lob) observed and measured each Survey and Year, by area (n_lob_North,…South). The number of locations (sites) at which lobsters were observed and measured (loc_lob_obs) and total locations surveyed (loc_surveyed) are indicated.**

| Year | Survey | n_lob | Ratio_MF | n_lob_North | n_lob_South | loc_lob_obs | loc_surveyed |
|---|---|---|---|---|---|---|---|
| 1989 | Mid | 816 | 0.99 | 125 | 691 | 73 | 542 |
| 1990 | Mid | 521 | 1.02 | 193 | 328 | 81 | 100 |
| 1991 | Mid | 655 | 0.89 | 248 | 407 | 84 | 100 |
| 1992 | Mid | 851 | 0.91 | 212 | 639 | 83 | 100 |
| 1993 | Mid | 334 | 1.06 | 77 | 257 | 67 | 100 |
| 1994 | Mid | 599 | 0.90 | 205 | 394 | 80 | 100 |
| 1995 | Mid | 458 | 0.97 | 165 | 293 | 69 | 100 |
| 1996 | Mid | 367 | 0.92 | 137 | 230 | 73 | 82 |
| 1997 | Mid | 457 | 1.18 | 227 | 230 | 67 | 82 |
| 1998 | Mid | 386 | 0.88 | 213 | 173 | 108 | 215 |
| 1999 | Mid | 375 | 0.88 | 132 | 243 | 56 | 82 |
| 2000 | Mid | 231 | 1.18 | 112 | 119 | 50 | 82 |
| 2001 | Mid | 148 | 0.97 | 28 | 120 | 48 | 82 |
| 2002 | Mid | 271 | 0.63 | 71 | 200 | 52 | 375 |
| 2003 | Mid | 499 | 0.88 | 286 | 213 | 94 | 158 |
| 2004 | Mid | 340 | 0.88 | 123 | 217 | 77 | 117 |
| 2005 | Mid | 232 | 0.86 | 72 | 160 | 54 | 86 |
| 2005 | Pre | 302 | 1.14 | 100 | 202 | 84 | 154 |
| 2006 | Mid | 303 | 1.16 | 68 | 235 | 56 | 80 |
| 2006 | Pre | 395 | 1.09 | 175 | 220 | 105 | 189 |
| 2007 | Mid | 339 | 0.97 | 130 | 209 | 78 | 106 |
| 2007 | Pre | 327 | 1.21 | 101 | 226 | 95 | 188 |
| 2008 | Mid | 207 | 0.95 | 59 | 148 | 56 | 103 |
| 2008 | Pre | 216 | 0.88 | 97 | 119 | 72 | 148 |
| 2009 | Mid | 238 | 0.92 | 114 | 124 | 56 | 74 |
| 2010 | Mid | 342 | 0.76 | 117 | 225 | 55 | 74 |
| 2011 | Mid | 380 | 0.90 | 109 | 271 | 61 | 73 |
| 2012 | Mid | 333 | 1.03 | 183 | 150 | 55 | 77 |
| 2013 | Mid | 173 | 1.16 | 73 | 100 | 41 | 74 |
| 2014 | Mid | 283 | 1.02 | 104 | 179 | 56 | 74 |
| 2014 | Pre | 436 | 1.12 | 146 | 290 | 92 | 130 |
| 2015 | Pre | 440 | 0.86 | 54 | 386 | 56 | 78 |
| 2016 | Pre | 130 | 0.69 | 52 | 78 | 49 | 77 |
| 2017 | Pre | 109 | 0.76 | 8 | 101 | 36 | 77 |
| 2018 | Mid | 178 | 1.14 | 74 | 104 | 52 | 78 |

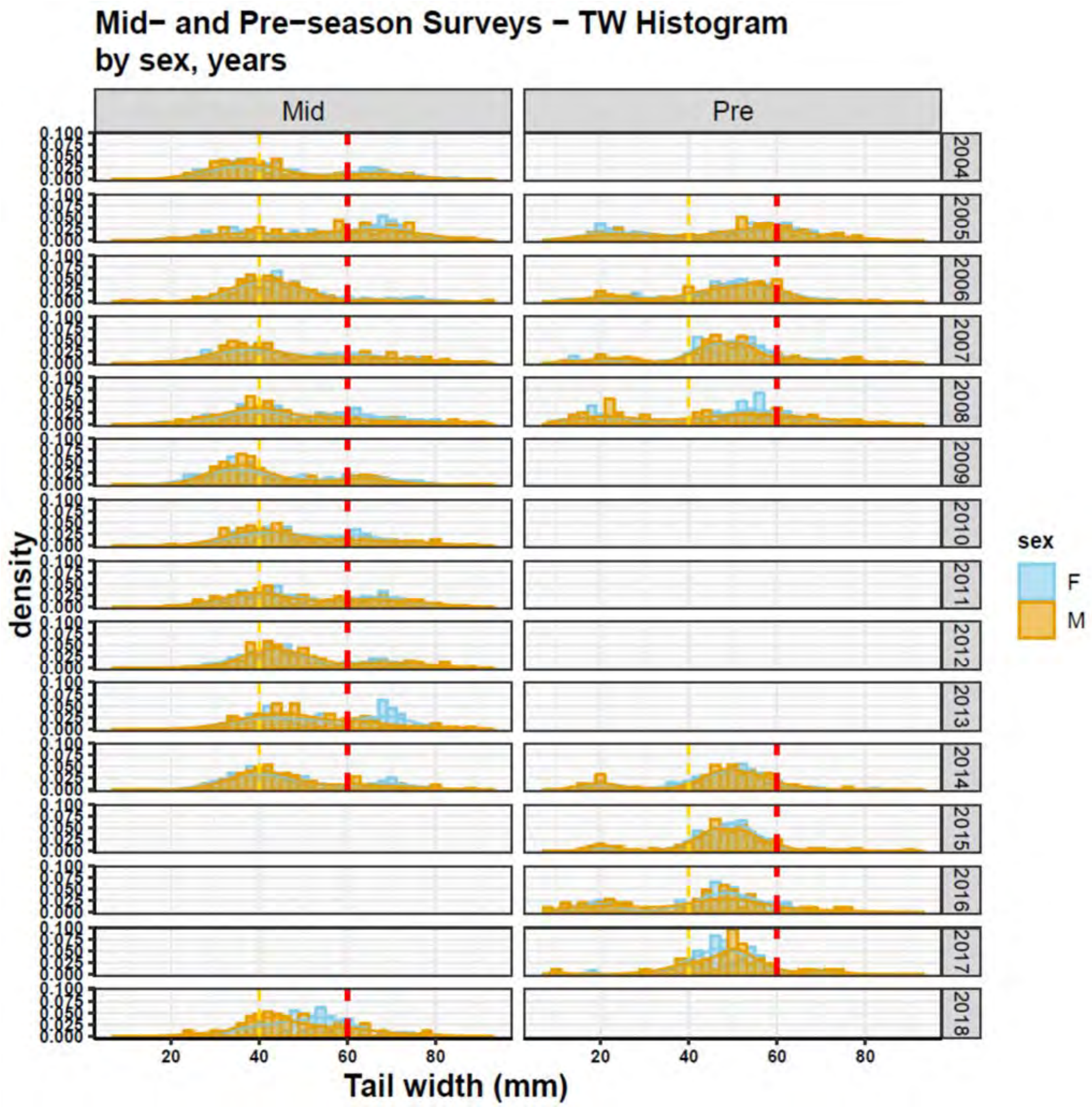



**Figure 1. Mid- (Jun/ Jul) and Pre-Season (Nov/ Dec) Surveys – Histogram (density distribution) of TS rock lobster tail width (TW) by sex, years (since 2004). Minimum legal size (converted. Males 60 mm TW, combined sexes 62 mm TW) and nominal 40 mm TW (estimated mean TW for 1+ cohort in Mid-season) are indicated (red and yellow dashed lines).**

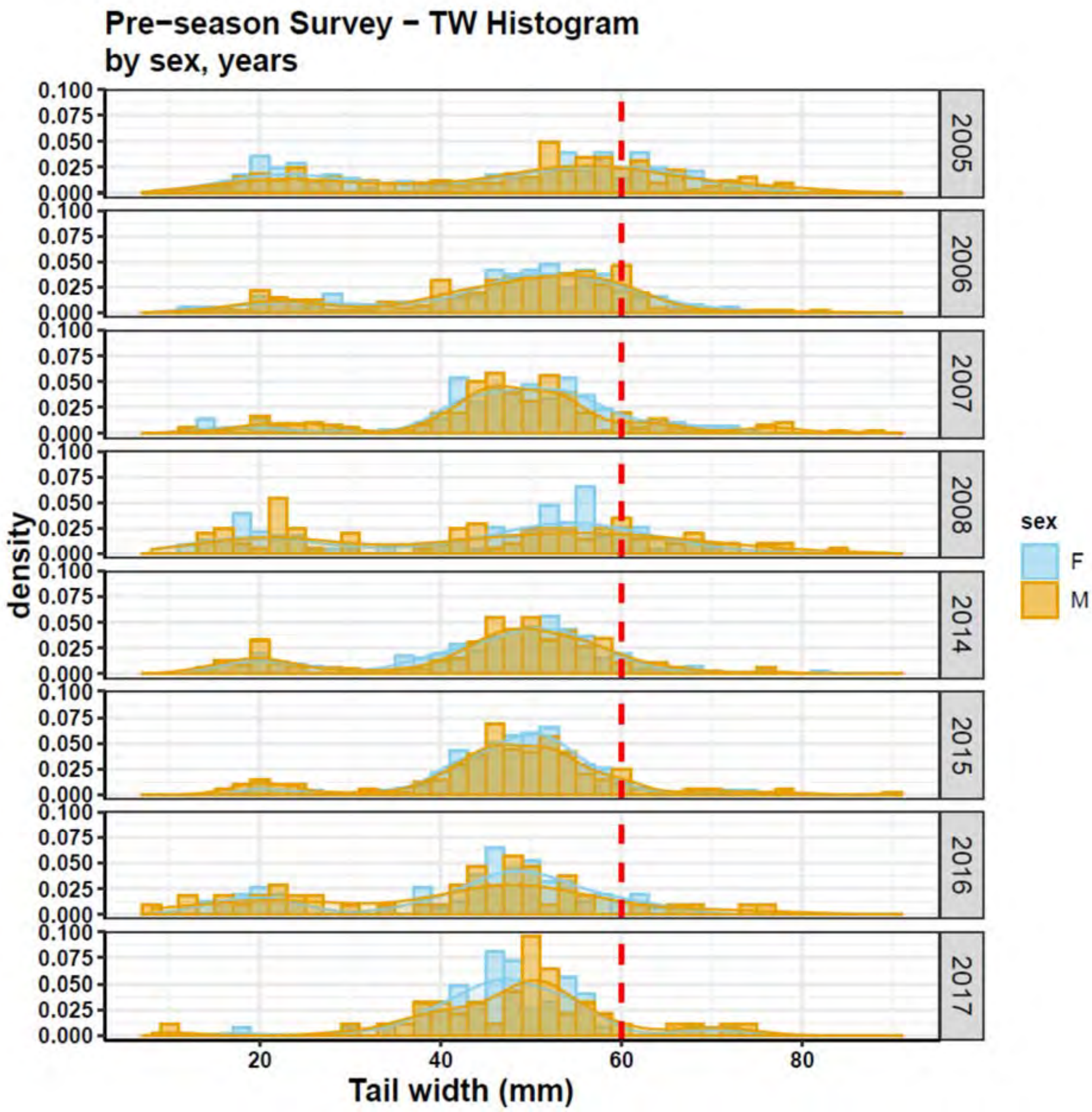



**Figure 2. Pre-Season Survey – Histogram (density distribution) of TS rock lobster tail width (TW) by sex, years (2005 to 2008, 2014 to 2017). Minimum legal size (converted. Males 60 mm TW, combined sexes 62 mm TW) is indicated (red dashed line).**

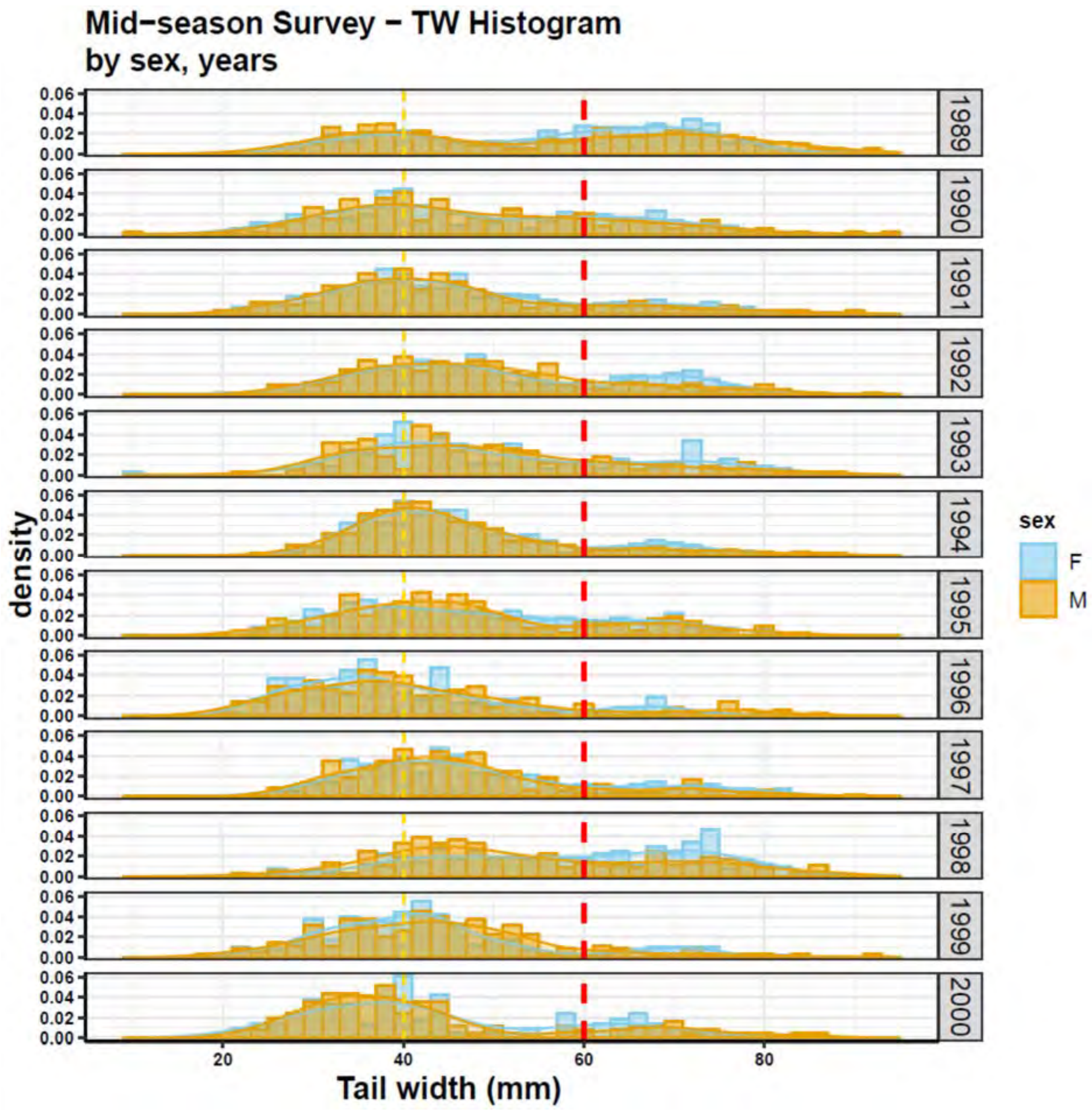



**Figure 3. Mid-Season Survey - Histogram (density distribution) of TS rock lobster tail width (TW) by sex, years (1989 to 2000). Minimum legal size (converted. Males 60 mm TW, combined sexes 62 mm TW) and nominal 40 mm TW (estimated mean TW for 1+ cohort in Mid-season) are indicated (red and yellow dashed lines).**

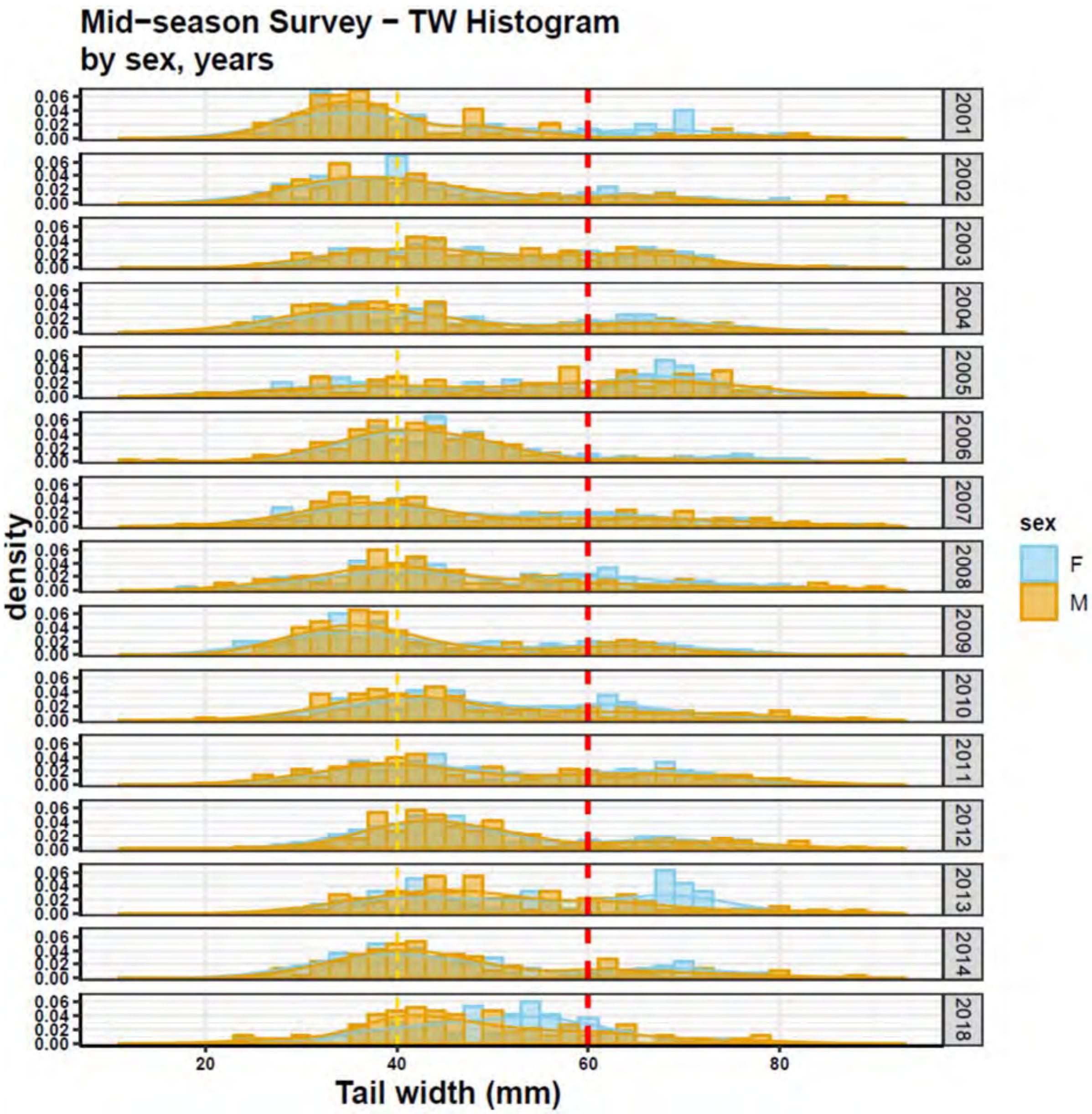



**Figure 4. Mid-Season Survey - Histogram (density distribution) of TS rock lobster tail width (TW) by sex, years (2000 to 2014, 2018). Minimum legal size (converted. Males 60 mm TW, combined sexes 62 mm TW) and nominal 40 mm TW (estimated mean TW for 1+ cohort in Mid-season) are indicated (red and yellow dashed lines).**

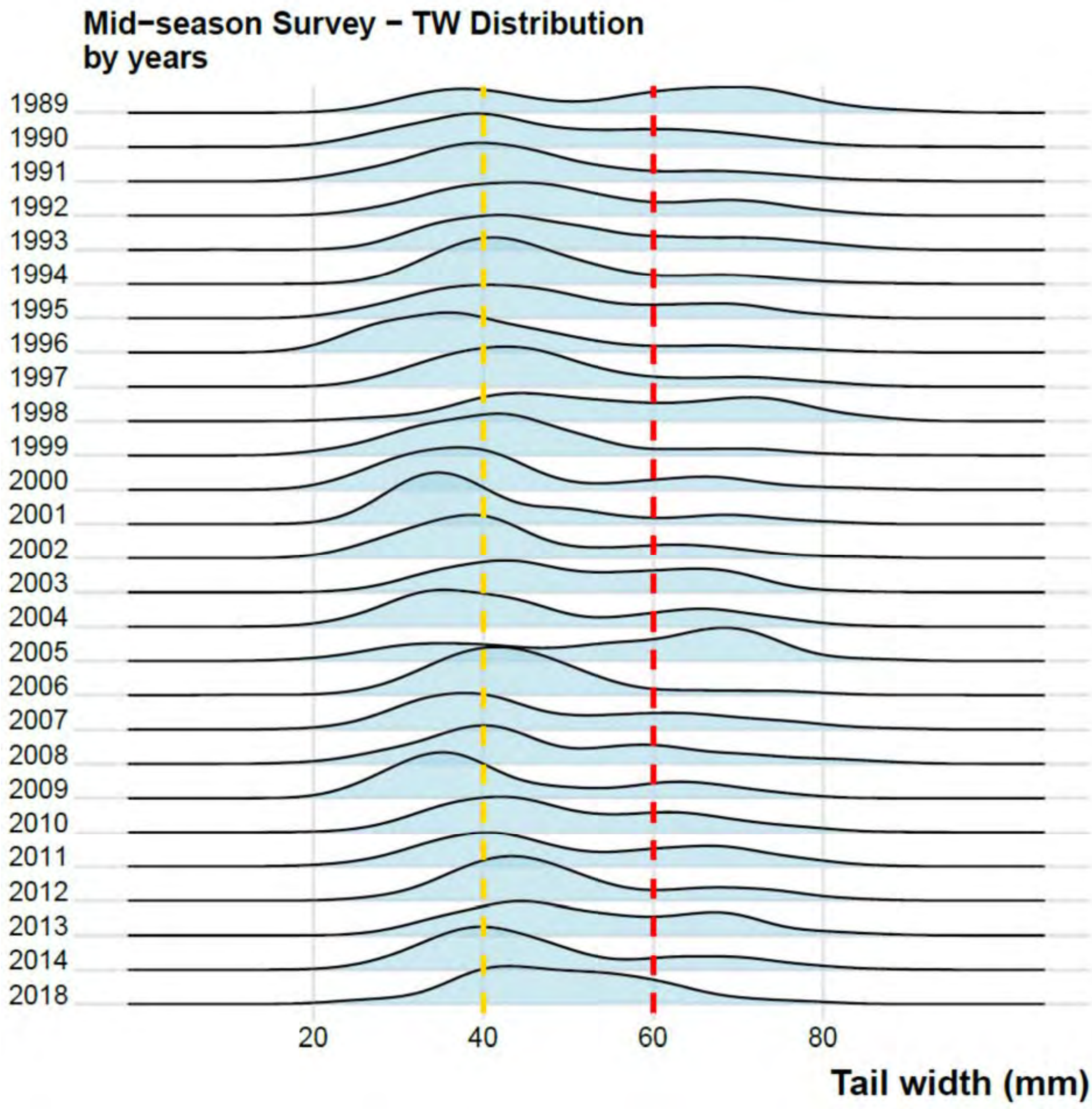
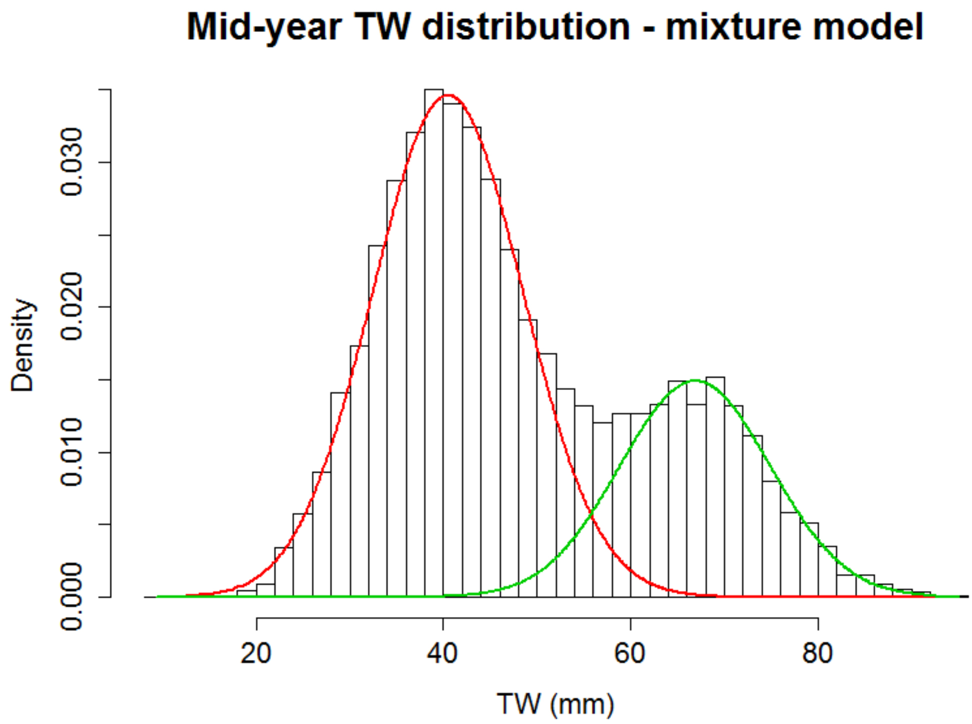



**Figure 5. Mid-Season Survey – Ridge plot showing TS rock lobster tail width (TW) density distributions for combined sexes, each year surveyed (1989 to 2018). Minimum legal size (converted. Males 60 mm TW, combined sexes 62 mm TW) and nominal 40 mm TW (estimated mean TW for 1+ cohort in Mid-season) are indicated (red and yellow dashed lines).**



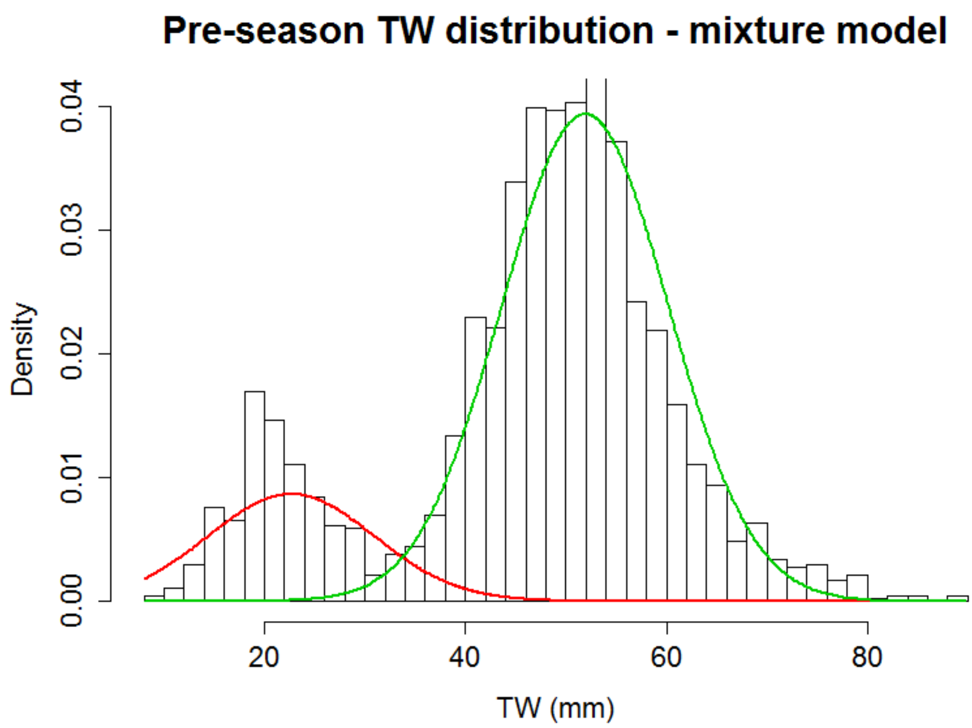




**Figure 6. Histogram and fitted normal component density distributions of TW (cohorts on average across all survey years) for Mid-Season (Mid-year) Survey (top plot), and Pre-Season Survey (bottom plot).**

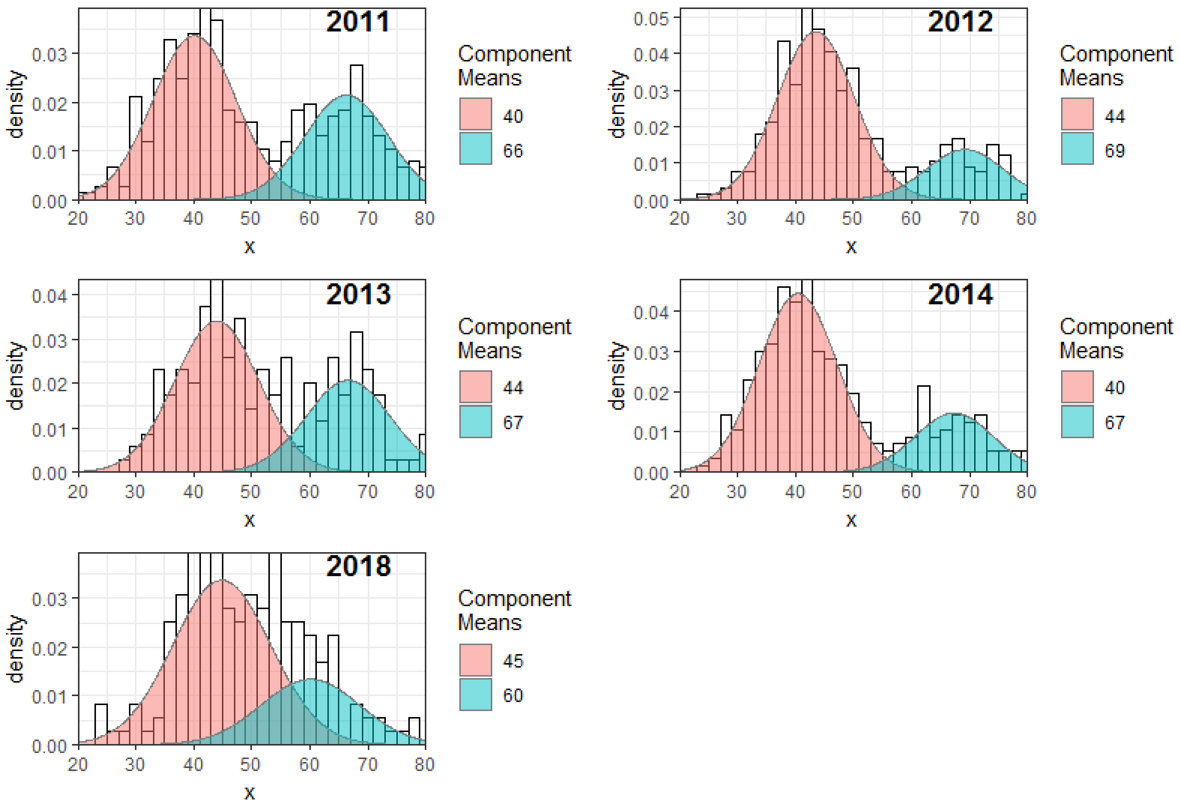



**Figure 7a. Mid-Season Survey - Histogram and fitted normal component density distributions of TW and mean estimates for recent years. x-axis: tail width (mm).**

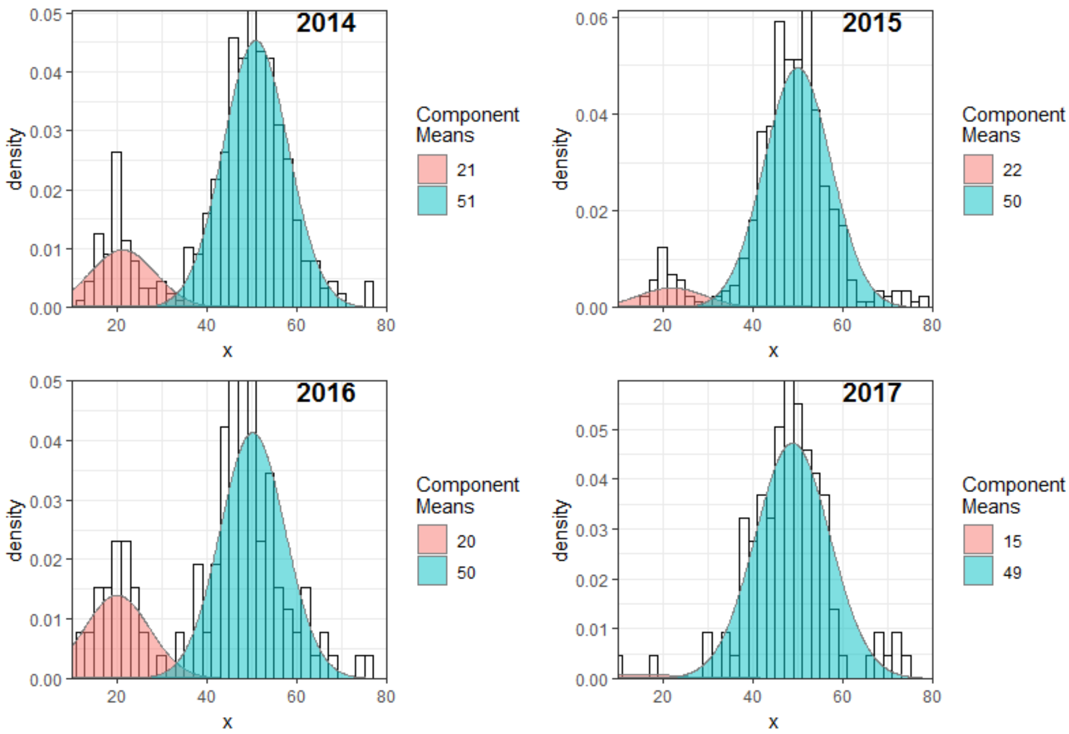



**Figure 7b. Pre-Season Survey - Histogram and fitted normal component density distributions of TW and mean estimates for recent years. x-axis: tail width (mm).**

## 2. Diagnostic plots

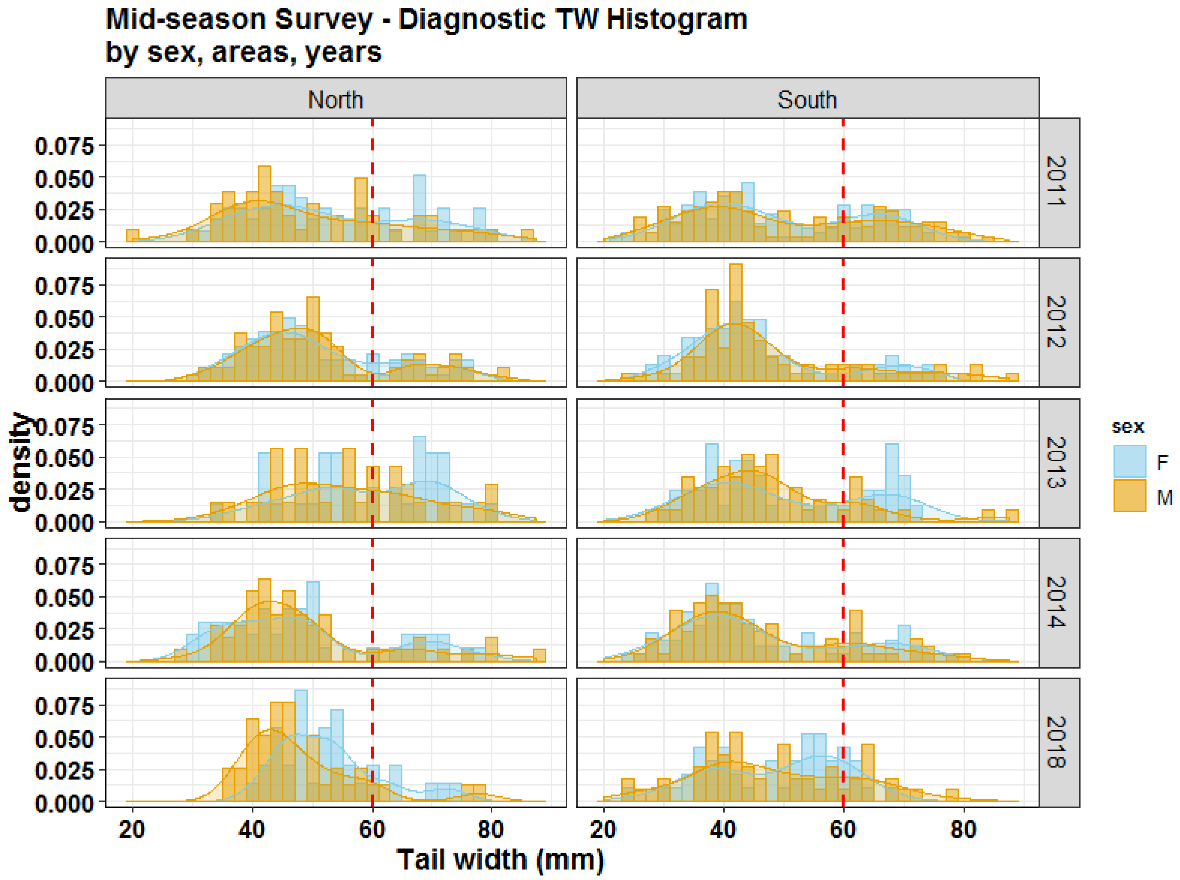



**Figure D1. Mid-Season Survey - Histogram (density distribution) of TS rock lobster tail width (TW) by sex and areas (North and South), 2018 and recent years surveyed.**

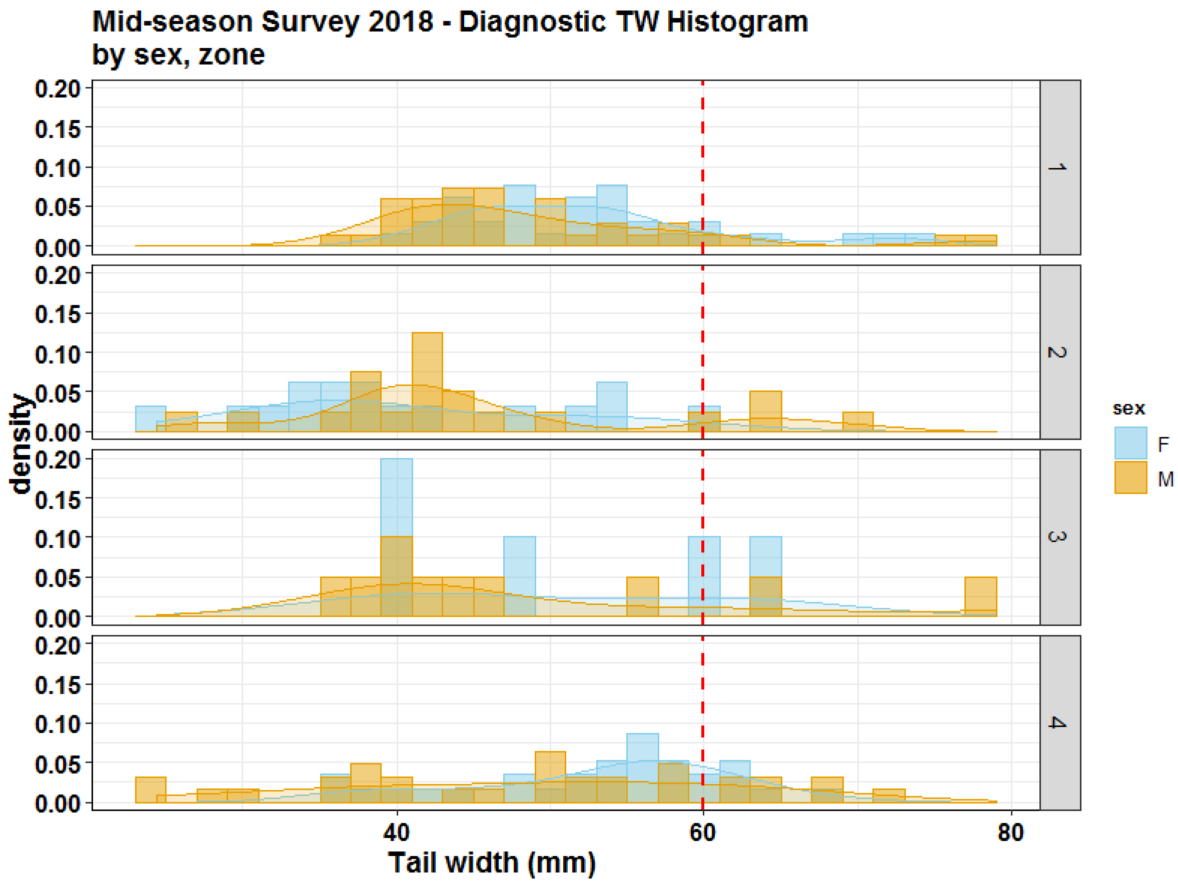



**Figure D2. Mid-Season Survey 2018 - Histogram (density distribution) of TS rock lobster tail width (TW) by sex and zone). Zones: 1=North West, 2=South West, 3=Central, 4=South East.**

## 3. Appendix

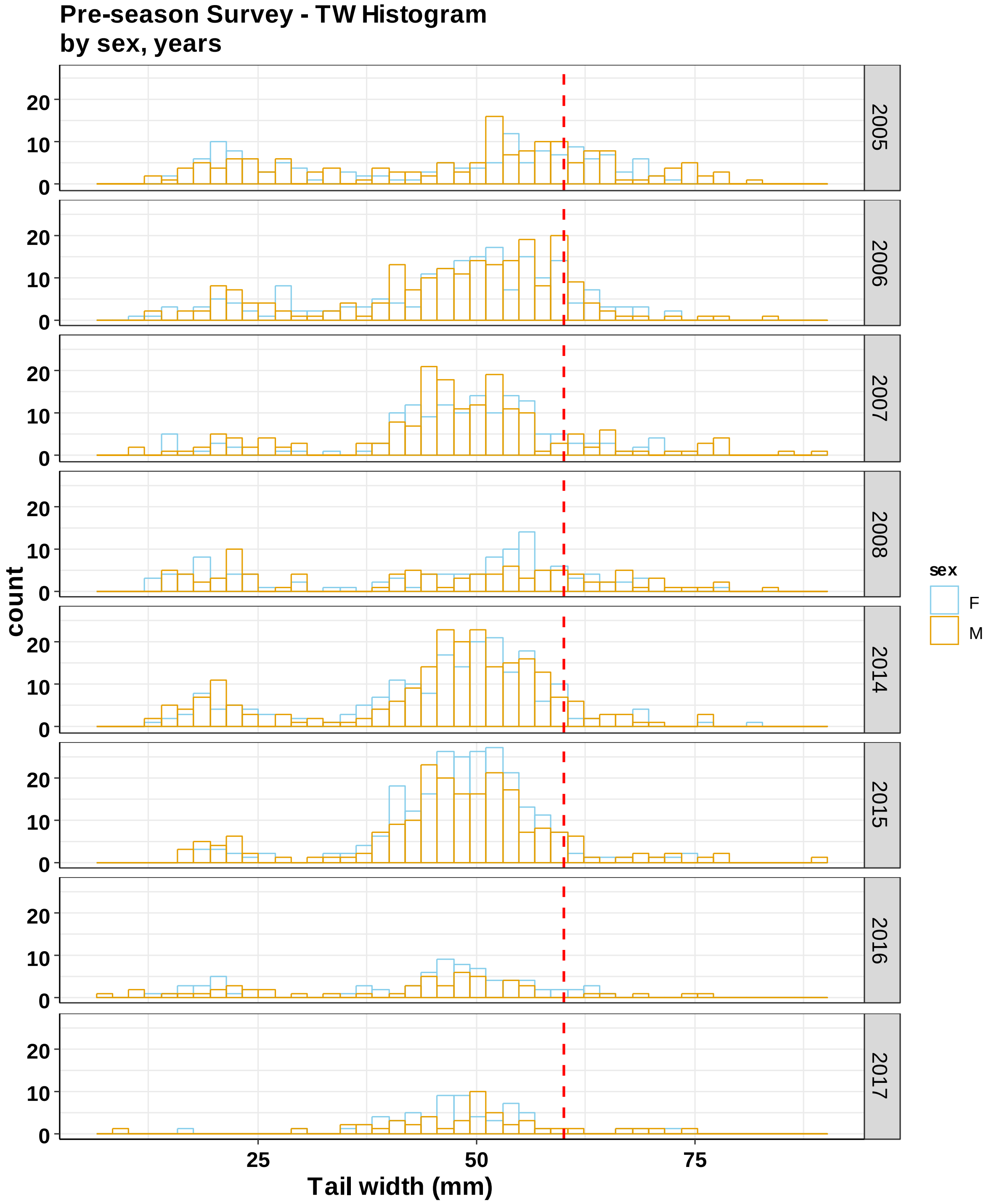



**Figure A1. Pre-Season Survey – Histogram (counts) of TS rock lobster TW by sex, years (2005 to 2008, 2014 to 2017).**

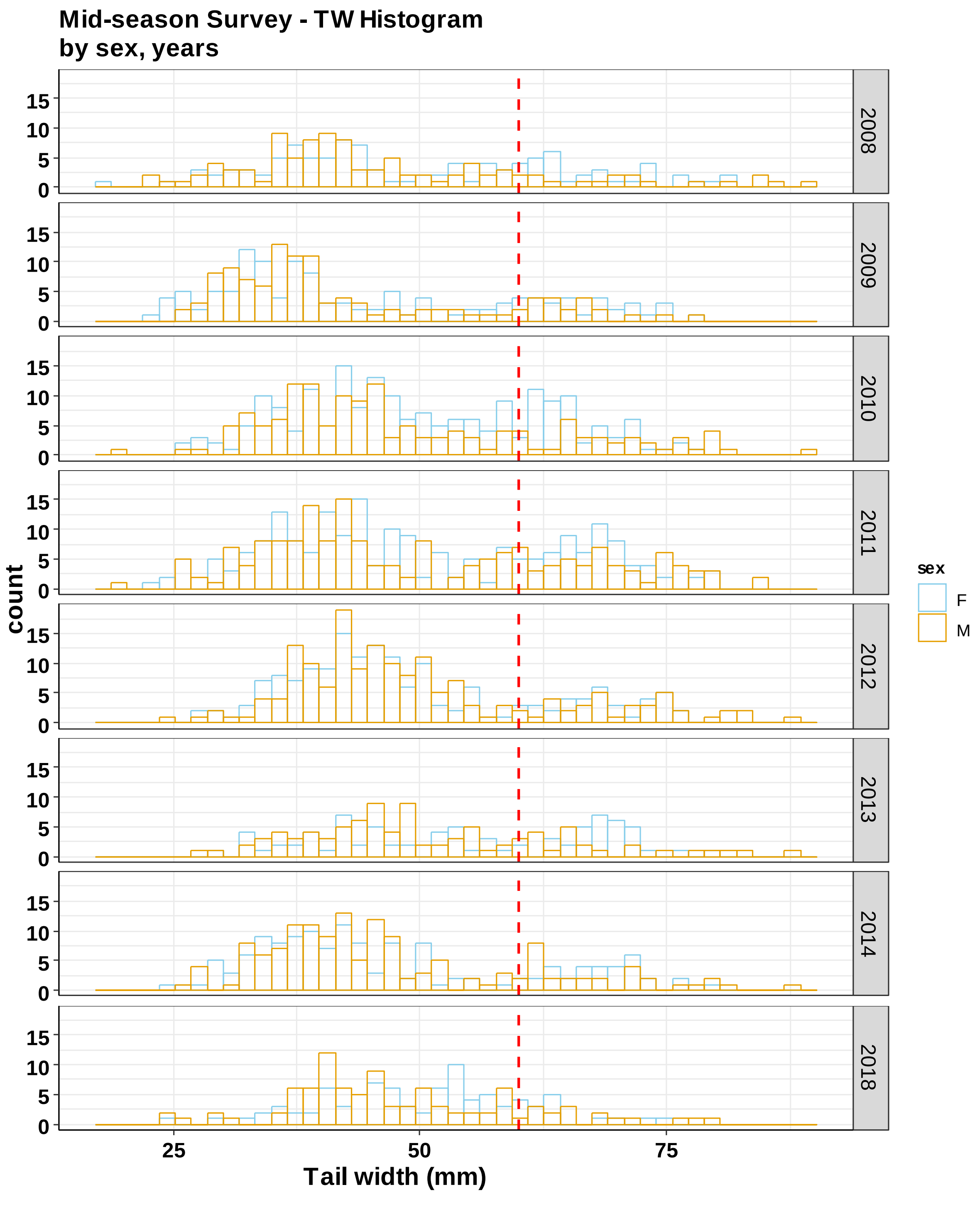



**Figure A2. Mid-Season Survey – Histogram (counts) of TS rock lobster TW by sex, years (2008 to 2014, 2018).**

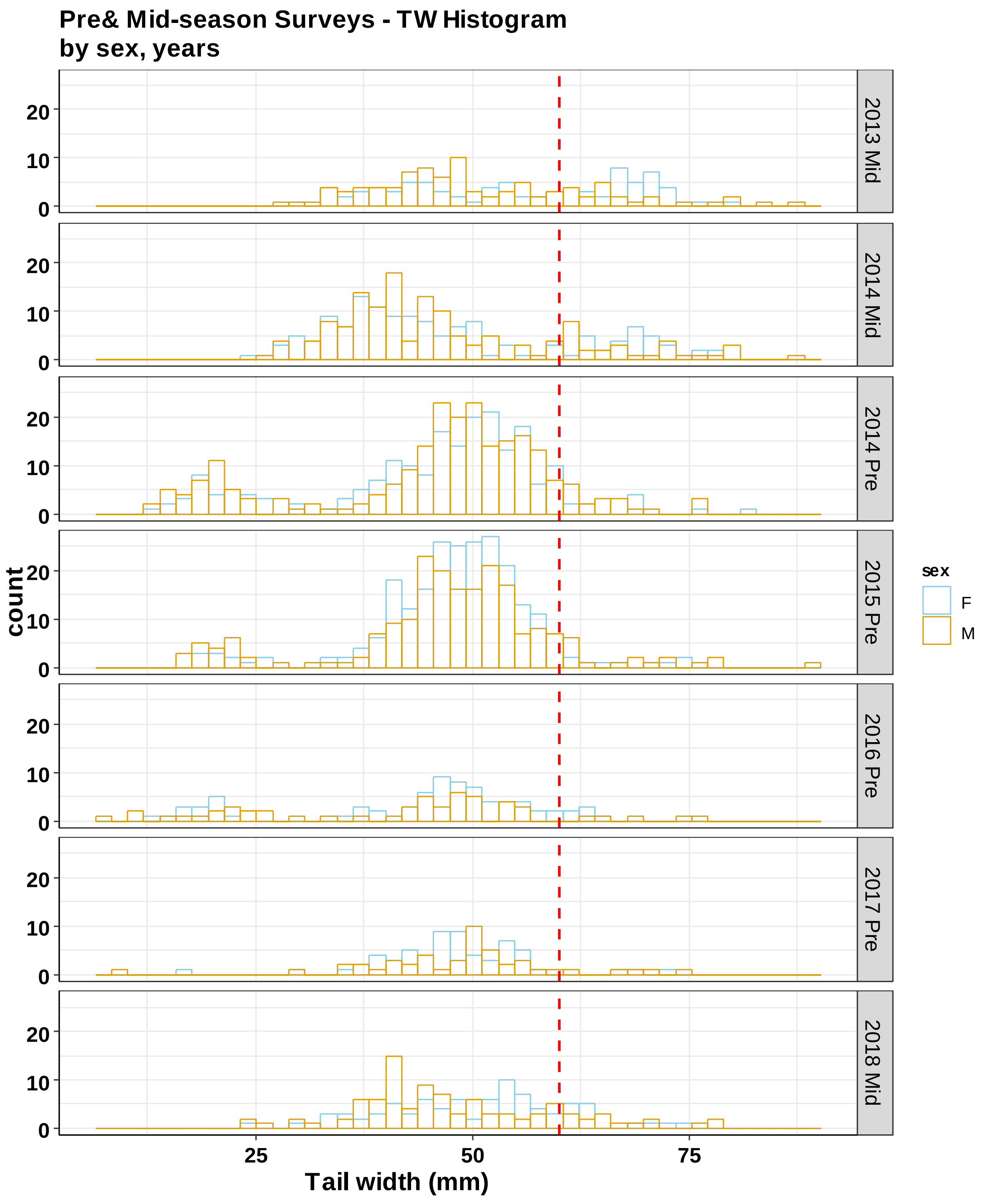



**Figure A3. Pre- and Mid-Season Surveys – Histogram (counts) of TS rock lobster TW by sex, years surveyed (since 2013).**

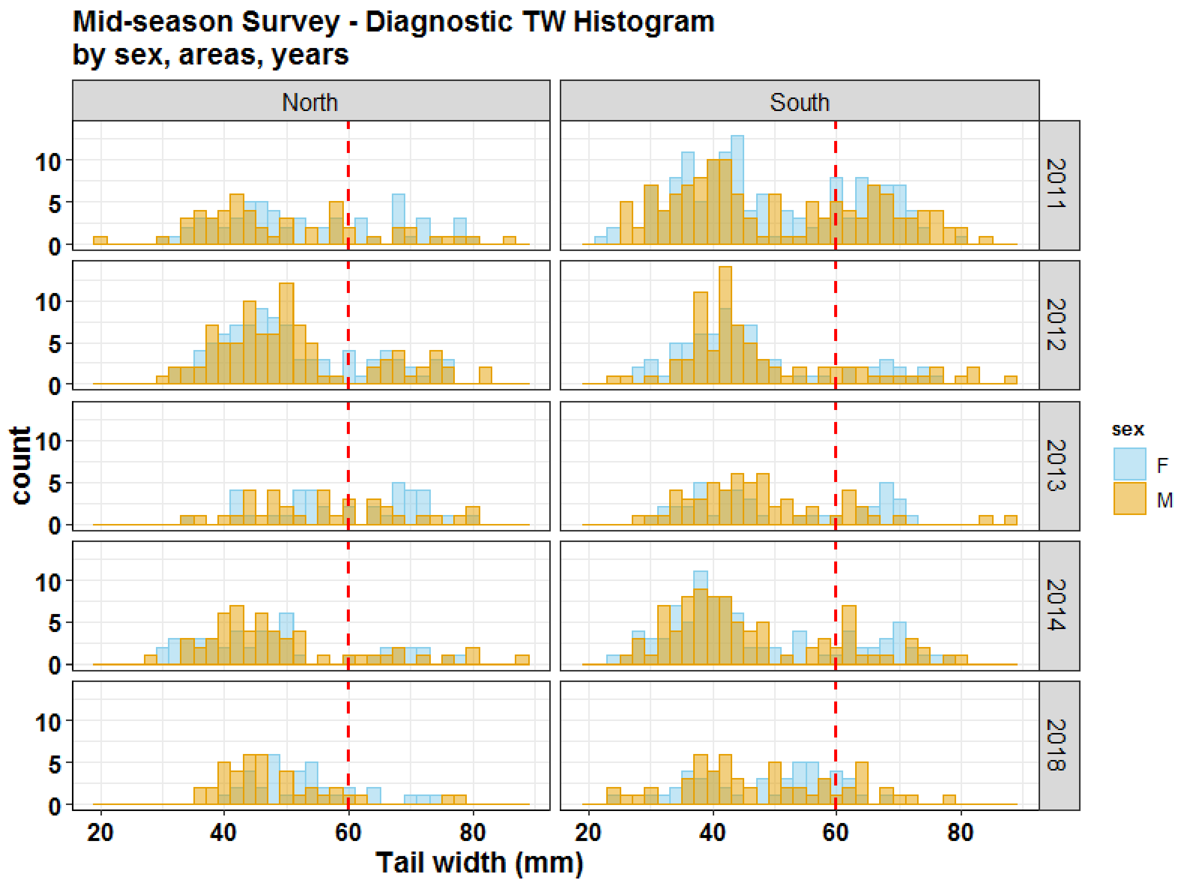



**Figure A4. Mid-Season Survey - Histogram (counts) of TS rock lobster tail width (TW) by sex and areas (North and South), 2018 and recent years surveyed.**

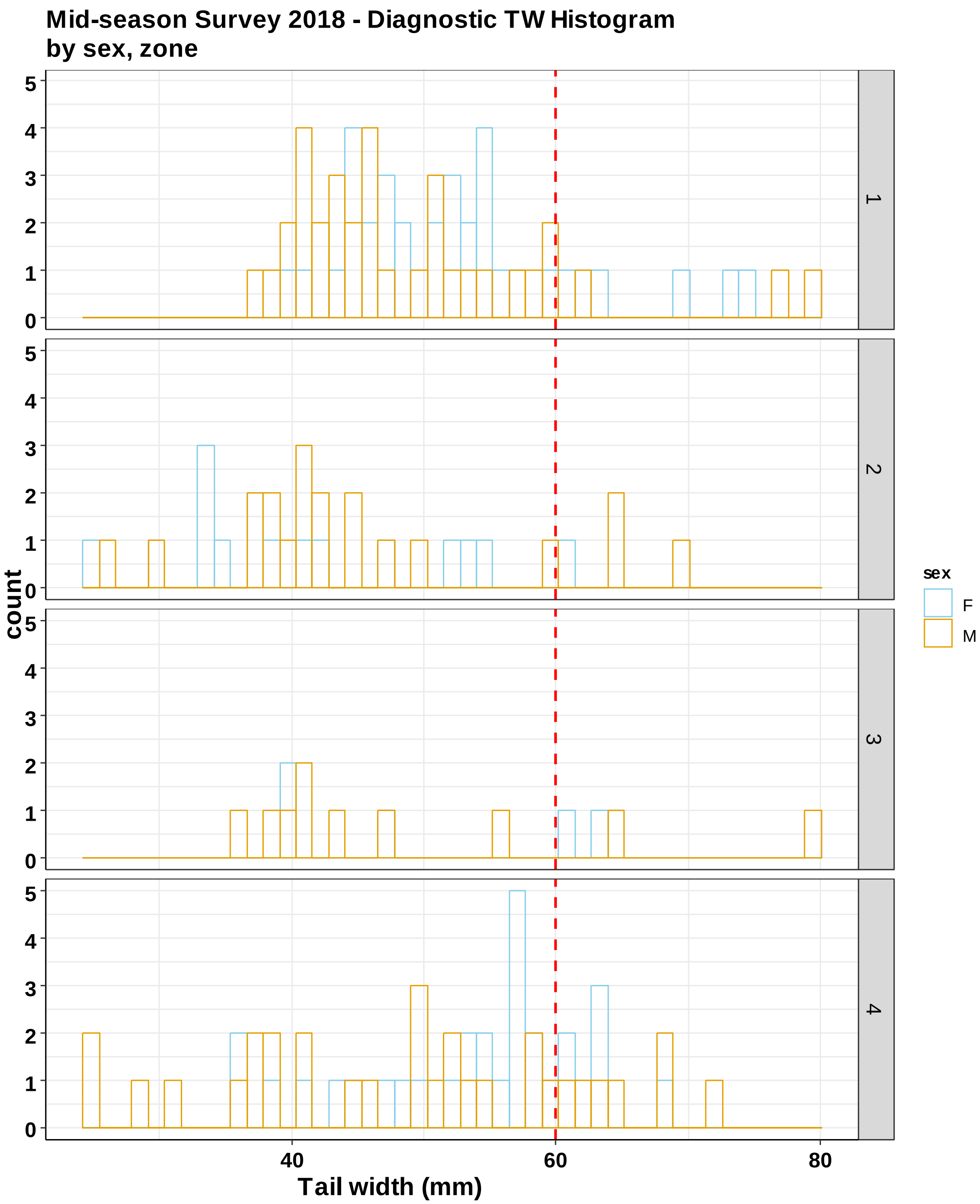



**Figure A5. Mid-Season Survey 2018 - Histogram (counts) of TS rock lobster tail width (TW) by sex and zone). Zones: 1=North West, 2=South West, 3=Central, 4=South East.**

# Torres Strait Rock Lobster Fishery – Summary of the Catch and Effort Data pertaining to the 2018 Fishing Season (Dec-17 to Jul-18)

*Robert Campbell, Eva Plaganyi, Roy Deng, Mark Tonks, Mick Haywood*

CSIRO Oceans and Atmosphere

October 2018

## 1. Introduction

This paper provides a summary of the catch and effort data pertaining to the Torres Strait Rock Lobster (TSRL) fishery during the 2018 fishing season. (Note, a fishing season begins on 1-December in a given year and extends through to 30-September the following year). In particular, as the 2018 ended early at the end of July, the paper provides a comparison of the annual trends in catch, effort and catch-rates in the eight months of December through to July so that the relative performance of the fishery during the 2018 season can be assessed relative to comparative periods of previous seasons. Note, this paper updates the previous paper presented to the Torres Strait Rock Lobster RAG in May 2018 (Campbell et al 2018).

## 2. Data

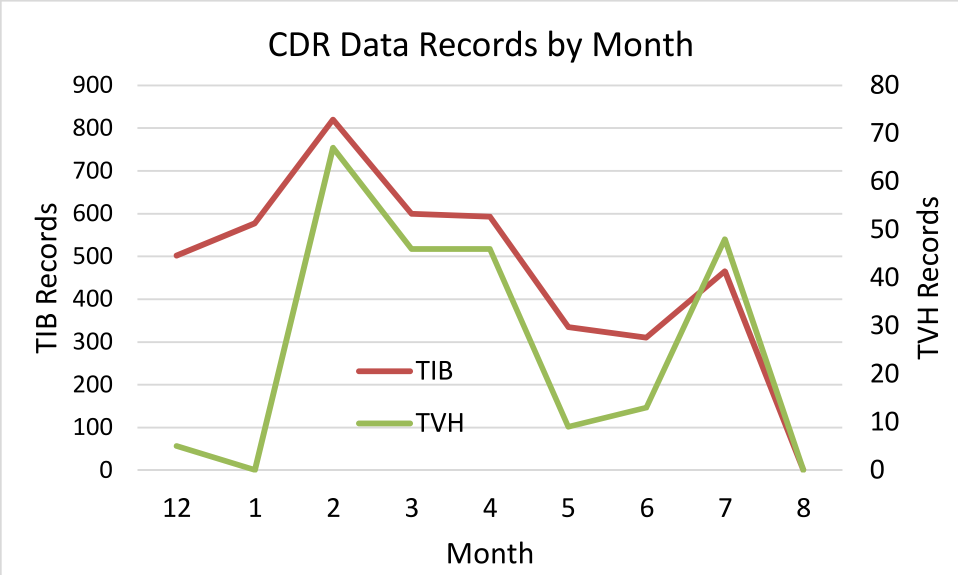
*TIB-Sector*

A new logbook, known as the Torres Strait Catch Disposal Record (TDB02), was introduced in the TSRL fishery on 1-December 2017. This logbook, which is mandatory to complete, records the catch weight of lobsters landed at the completion of all fishing trips. As well as information related to the fish receiver, the logbook also records information related to the fisher (name, boat symbol, etc), the sector of the fishery that the fisher operated (e.g. TIB or TVH) and the process state of the catch (e.g. whole, live or tailed). Additional information related to fishing effort (e.g. days fished, number of fishers) together with the area fished and methods used is currently only optional.

The TDB02 logbook replaces the Torres Strait Seafood Buyers and Processors Docket Book (TDB01) which had been used in the TIB sector to record the catch sold by fishers at the end of a fishing trip. Completion of this docket-book had only been voluntary and in several fishing seasons (2013-2016) the catch data for the TIB sector was supplemented with aggregate catch data obtained directly from several processors. The introduction of the compulsory TDB02 should rectify this past issue. Hopefully, the TDB02 logbook will also rectify previous issues which were associated with the use of the TDB01 docket-book such as the double recording of catches (see Campbell and Pease 2017). Whether or not the introduction of the compulsory TDB02 logbook will lead to an increase in the reporting levels of the TIB catch will also need to be assessed.

Data related to the TDB02 CDR logbook was last obtained from AFMA on 26 September 2018 while the last batch of data related to the TDB01 docket-book was obtained from AFMA in late October 2017. For the data summaries presented in this paper for the TIB sector, all data before December 2017 is based from this latter data while all data since December 2017 is taken from the TDB02 CDR logbook. The TDB01 docket-book data may be incomplete to some extent for the last few months up until November 2017; however the TDB02 data for

Figure 1. Number of data records per month for each sector of the TSRL fishery present in the TDB02 CDR data sent by AFMA on 25-Sep-18. Note, the month of each record is based on the trip-end date. The date of the last trip/shot date recorded for the TIB and TVH sectors is 30-Jul-18 and 24-Jul-18 respectively.




the 2018 season is considered to be complete (c.f. Figure 1). A more detailed summary of the TIB data for the period up to October 2017 is provided in Campbell et al (2017a).

*TVH-Sector*

Together with the catch landed by the TIB-sector of the TSRL fishery, the new Torres Strait Catch Disposal Record (TDB02), introduced in the TSRL fishery at the start of November 2017, also records the catch landed by the TVH-sector. However, unlike for the TIB-sector, catch and effort data related to the TVH sector also continues to be recorded in the Torres Strait Tropical Rock Lobster Fishery Daily Fishing Log (TRL04).

Data related to the TRL04 logbook for the 2018 season was obtained from AFMA on 25 September 2018. For the data summaries presented in this paper for the TVH sector all data is based on information recorded in the TRL04 logbook. As with the TSDB01 logbook, the TRL04 logbook data may also be incomplete to some extent up until November 2017, while the TRL04 data (as with the TDB02 logbook) for the 2018 season is considered to be complete (c.f. Figure 1). A more detailed summary of the TVH data for the period up to October 2017 is provided in Campbell et al (2017b).

## 3. Catch by Season

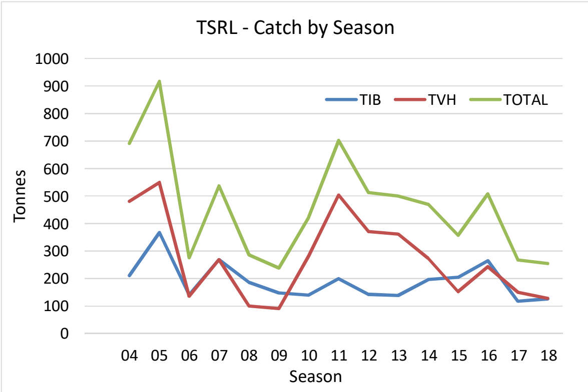
A comparison of the estimated total catch by sector for the seasons 2004 to 2018 is shown in Figure 2. As the TVH catch is recorded in both the TRL04 logbook and the TDB02 logbook, two estimates for the 2018 season are provided for this sector. The small difference noted in the estimated TVH catch from these two logbooks is likely due to the fact that TRL04 weights are often estimated compared to more accurate weighing on land and a discrepancy of between 5-10% can usually be expected. Some differences in these catch estimates may also be due to differences in the times that AFMA receive and enter data from the two logbook during the season.

Figure 2. Time-series of total catch by fishing season (December-November) and sector since 2004. TIB data is based on TDB01 docket-book and TDB02 CDR data, while TVH data is based on TRL04 logbook data. Data for 2018 only covers the period December-July as the fishery was closed at the end of July-2018.

.

| SEASON | TIB | TVH | TOTAL |
|---|---|---|---|
| 2004 | 210.4 | 481.1 | 691.5 |
| 2005 | 367.6 | 549.9 | 917.6 |
| 2006 | 140.5 | 135.5 | 275.9 |
| 2007 | 268.7 | 268.6 | 537.3 |
| 2008 | 185.7 | 100.4 | 286.1 |
| 2009 | 147.8 | 91.1 | 238.9 |
| 2010 | 140.0 | 282.6 | 422.7 |
| 2011 | 199.1 | 503.5 | 702.6 |
| 2012 | 142.4 | 370.5 | 512.9 |
| 2013 | 138.4 | 361.7 | 500.1 |
| 2014 | 196.8 | 273.2 | 470.0 |
| 2015 | 204.7 | 152.7 | 357.4 |
| 2016 | 264.7 | 243.0 | 507.7 |
| 2017 | 117.9 | 149.7 | 267.6 |
| 2018 | 126.5 | 128.3 | 254.8 |

NB. TVH (2018) =134.1 based on CDR




The reported catch by month for each sector of the TSRL for the 2004-2018 fishing seasons is shown in Table 1. The catch by month for the TVH sector is based on information reported in the TRLO04 logbook, while the catches for the TIB sector are based on information reported in the TBD01 docket-book and TDB02 CDR. Furthermore, for the TIB sector the catch by month for the 2013-2016 fishing seasons is an estimate as the catch month is not known for a substantive portion, *P,* of the total catch in these seasons (*P*=39%, 34%, 33%, 55% respectively). These relate to the aggregate catches reported by several processors on a seasonal basis to account for missing docket-book records. For these seasons the catch within each month was estimated by raising the known catch in each month by the factor $R= 1/(1-P)$. This assumes that the distribution of the catches by month in the aggregate catch data is the same as the distribution within the docket-book recorded catches.

Based on the catch-by-month estimates provided in Table 1, the time-series of catch by month for the eight months December-to- July is shown in Figure 3 for each sector of the TSRL over the seasons 2004-2018.

Table 1. Catch by month (kilograms) for (a) the TIB sector, (b) the TVH sector and (c) the total TSRL fishery for the 2004-2018 fishing seasons. Note, the catch by month for the TVH is based on information reported in the TRL04 logbook, while the catches for the TIB sector are based on information reported in the TBD01 docket-book and TDB02 CDR. Furthermore, for the TIB sector the catch by month for the 2013-2016 fishing seasons is an estimate as the catch month is not known for a substantive portion *P* of the total catch in these seasons (*P*=39%, 34%, 33%, 55% respectively). For these seasons the catch within each month was estimated by raising the known catch in each month by the factor *R*= *1/(1-P*).

(a) TIB (From TBD01 and TDB02 logbooks

| SEASON | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2004 | | 15,542 | 24,309 | 35,574 | 17,737 | 30,356 | 28,516 | 26,449 | 18,976 | 12,873 | 24 | 25 | 210,381 |
| 2005 | 21,648 | 15,098 | 50,625 | 58,221 | 47,575 | 56,758 | 43,061 | 34,474 | 23,682 | 16,088 | 314 | 71 | 367,615 |
| 2006 | 12,507 | 9,447 | 24,018 | 26,814 | 19,091 | 18,380 | 9,814 | 9,910 | 7,672 | 2,747 | 0 | 51 | 140,451 |
| 2007 | 19,002 | 24,941 | 24,716 | 62,040 | 29,185 | 33,759 | 29,025 | 23,193 | 13,907 | 8,920 | 0 | 0 | 268,688 |
| 2008 | 10,435 | 13,461 | 31,237 | 36,127 | 24,110 | 16,711 | 14,805 | 23,516 | 9,277 | 5,969 | 18 | 0 | 185,666 |
| 2009 | 9,716 | 13,273 | 20,547 | 23,103 | 23,733 | 15,647 | 13,242 | 15,393 | 7,811 | 4,819 | 529 | 0 | 147,813 |
| 2010 | 5,764 | 6,198 | 21,259 | 15,829 | 14,995 | 12,180 | 16,348 | 19,073 | 17,001 | 9,782 | 1,610 | 0 | 140,039 |
| 2011 | 6,929 | 18,215 | 30,141 | 49,767 | 20,400 | 23,990 | 18,686 | 18,856 | 8,858 | 3,218 | 0 | 0 | 199,060 |
| 2012 | 9,036 | 13,403 | 19,028 | 24,718 | 19,606 | 9,689 | 22,874 | 11,194 | 10,836 | 1,996 | 0 | 0 | 142,380 |
| 2013 | 3,080 | 1,371 | 15,940 | 13,421 | 20,778 | 18,606 | 16,324 | 18,656 | 14,425 | 15,837 | 0 | 0 | 138,439 |
| 2014 | 10,773 | 13,339 | 18,379 | 38,920 | 28,385 | 25,455 | 16,908 | 17,455 | 17,388 | 9,639 | 187 | 0 | 196,827 |
| 2015 | 18,513 | 9,495 | 31,813 | 21,672 | 27,456 | 17,212 | 45,680 | 13,204 | 11,819 | 7,512 | 283 | 0 | 204,659 |
| 2016 | 10,156 | 15,604 | 52,833 | 36,406 | 23,176 | 34,192 | 33,687 | 25,025 | 22,438 | 10,821 | 220 | 168 | 264,725 |
| 2017 | 11,536 | 8,290 | 23,339 | 15,831 | 11,697 | 14,959 | 7,476 | 9,730 | 10,803 | 4,075 | 155 | 0 | 117,891 |
| 2018 | 15,097 | 13,067 | 20,950 | 19,104 | 17,075 | 10,137 | 10,629 | 20,418 | 0 | 0 | 0 | 0 | 126,477 |

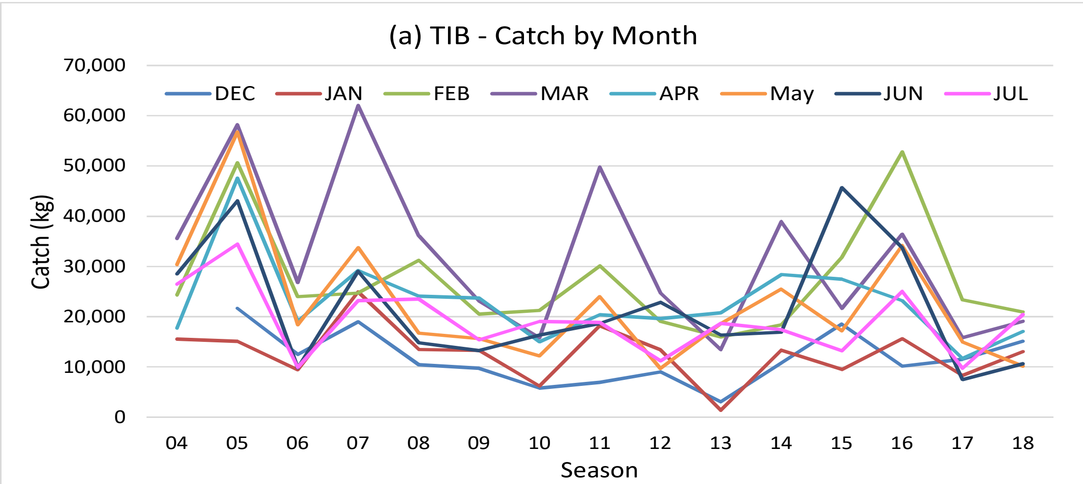
(b) TVH (From TRL04 logbook)

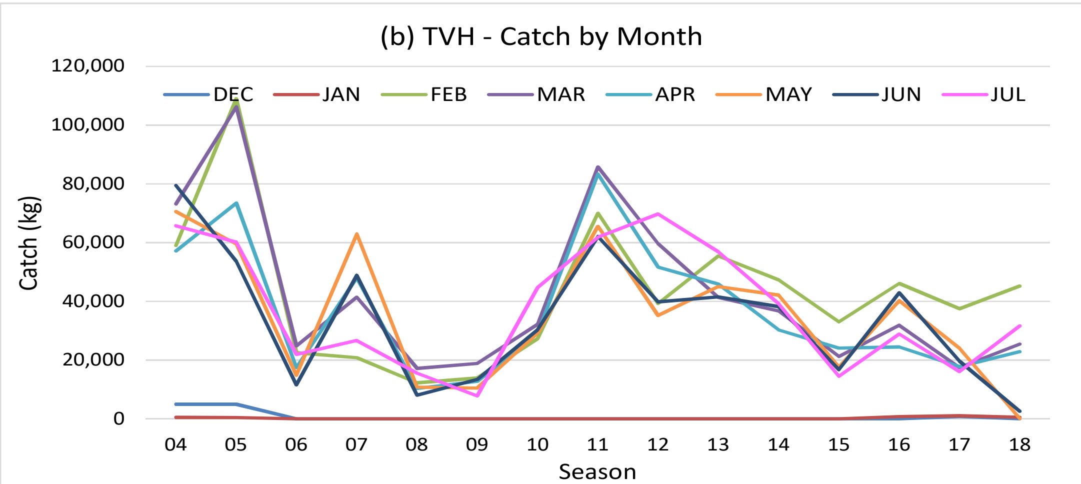
| SEASON | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2004 | 4,949 | 452 | 58,965 | 73,180 | 57,142 | 70,551 | 79,438 | 65,766 | 48,014 | 22,625 | 0 | 0 | 481,082 |
| 2005 | 4,984 | 398 | 108,962 | 106,276 | 73,510 | 59,475 | 53,618 | 60,103 | 51,795 | 30,814 | 0 | 0 | 549,935 |
| 2006 | 25 | 0 | 22,512 | 24,860 | 17,491 | 14,798 | 11,490 | 21,952 | 16,756 | 5,589 | 0 | 0 | 135,473 |
| 2007 | 0 | 0 | 20,768 | 41,389 | 47,980 | 62,933 | 48,836 | 26,689 | 13,633 | 6,368 | 0 | 0 | 268,596 |
| 2008 | 0 | 0 | 12,285 | 17,166 | 10,334 | 10,809 | 7,997 | 15,482 | 16,819 | 9,545 | 0 | 0 | 100,437 |
| 2009 | 0 | 0 | 13,905 | 18,881 | 12,748 | 10,479 | 13,408 | 7,824 | 10,345 | 3,470 | 0 | 0 | 91,060 |
| 2010 | 0 | 0 | 27,311 | 32,164 | 29,202 | 29,192 | 30,315 | 44,734 | 52,026 | 37,670 | 0 | 0 | 282,614 |
| 2011 | 0 | 0 | 69,994 | 85,730 | 83,334 | 65,515 | 62,084 | 61,867 | 45,097 | 29,913 | 0 | 0 | 503,534 |
| 2012 | 0 | 0 | 39,228 | 59,636 | 51,696 | 35,159 | 39,807 | 69,718 | 48,959 | 26,280 | 0 | 0 | 370,483 |
| 2013 | 0 | 0 | 55,428 | 41,275 | 45,929 | 45,030 | 41,502 | 56,818 | 47,621 | 28,058 | 0 | 0 | 361,661 |
| 2014 | 0 | 0 | 47,338 | 36,706 | 30,230 | 42,088 | 38,160 | 39,061 | 23,418 | 16,213 | 0 | 0 | 273,214 |
| 2015 | 0 | 0 | 32,992 | 21,166 | 24,051 | 17,623 | 16,745 | 14,460 | 19,782 | 5,891 | 0 | 0 | 152,710 |
| 2016 | 0 | 750 | 46,101 | 31,830 | 24,474 | 40,200 | 42,871 | 28,854 | 18,851 | 9,079 | 0 | 0 | 243,010 |
| 2017 | 690 | 1,051 | 37,432 | 17,478 | 17,701 | 23,982 | 19,559 | 16,105 | 12,939 | 2,801 | 0 | 0 | 149,738 |
| 2018 | 0 | 565 | 45,187 | 25,440 | 22,791 | 101 | 2,628 | 31,612 | 0 | 0 | 0 | 0 | 128,324 |
| TDB02 | 34 | 0 | 42,429 | 28,610 | 23,390 | 3,115 | 2,967 | 33,563 | | | | | 134,108 |

(c) TOTAL

| SEASON | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2004 | 4,949 | 15,994 | 83,274 | 108,754 | 74,879 | 100,907 | 107,954 | 92,215 | 66,990 | 35,498 | 24 | 25 | 691,463 |
| 2005 | 26,632 | 15,496 | 159,587 | 164,497 | 121,085 | 116,233 | 96,679 | 94,577 | 75,477 | 46,902 | 314 | 71 | 917,550 |
| 2006 | 12,532 | 9,447 | 46,530 | 51,674 | 36,582 | 33,178 | 21,304 | 31,862 | 24,428 | 8,336 | 0 | 51 | 275,924 |
| 2007 | 19,002 | 24,941 | 45,484 | 103,429 | 77,165 | 96,692 | 77,861 | 49,882 | 27,540 | 15,288 | 0 | 0 | 537,284 |
| 2008 | 10,435 | 13,461 | 43,522 | 53,293 | 34,444 | 27,520 | 22,802 | 38,998 | 26,096 | 15,514 | 18 | 0 | 286,103 |
| 2009 | 9,716 | 13,273 | 34,452 | 41,984 | 36,481 | 26,126 | 26,650 | 23,217 | 18,156 | 8,289 | 529 | 0 | 238,873 |
| 2010 | 5,764 | 6,198 | 48,570 | 47,993 | 44,197 | 41,372 | 46,663 | 63,807 | 69,027 | 47,452 | 1,610 | 0 | 422,653 |
| 2011 | 6,929 | 18,215 | 100,135 | 135,497 | 103,734 | 89,505 | 80,770 | 80,723 | 53,955 | 33,131 | 0 | 0 | 702,594 |
| 2012 | 9,036 | 13,403 | 58,256 | 84,354 | 71,302 | 44,848 | 62,681 | 80,912 | 59,795 | 28,276 | 0 | 0 | 512,863 |
| 2013 | 3,080 | 1,371 | 71,368 | 54,696 | 66,707 | 63,636 | 57,826 | 75,474 | 62,046 | 43,895 | 0 | 0 | 500,100 |
| 2014 | 10,773 | 13,339 | 65,717 | 75,626 | 58,615 | 67,543 | 55,068 | 56,516 | 40,806 | 25,852 | 187 | 0 | 470,041 |
| 2015 | 18,513 | 9,495 | 64,805 | 42,838 | 51,507 | 34,835 | 62,425 | 27,664 | 31,601 | 13,403 | 283 | 0 | 357,369 |
| 2016 | 10,156 | 16,354 | 98,934 | 68,236 | 47,650 | 74,392 | 76,558 | 53,879 | 41,289 | 19,900 | 220 | 168 | 507,735 |
| 2017 | 12,226 | 9,341 | 60,771 | 33,309 | 29,398 | 38,941 | 27,035 | 25,835 | 23,742 | 6,876 | 155 | 0 | 267,629 |
| 2018 | 15,097 | 13,632 | 66,137 | 44,544 | 39,866 | 10,238 | 13,257 | 52,030 | 0 | 0 | 0 | 0 | 254,801 |

Figure 3. Time-series of catch by month for the eight months December-to-July for (a) the TIB sector, (b) the TVH sector and (c) the total TSRL fishery. Note, the catch by month for the TVH is based on information reported in the TRL04 logbook, while the catches for the TIB sector are based on information reported in the TBD01 docket-book and TDB02 CDR. Furthermore, the TIB sector the catch by month for the 2013-2016 fishing seasons is an estimate as the catch month is not known for a substantive portion *P* of the total catch in these seasons (*P*=39%, 34%, 33%, 55% respectively). For these seasons the catch within each month was estimated by raising the known catch in each month by the factor *R= 1/(1-P*).



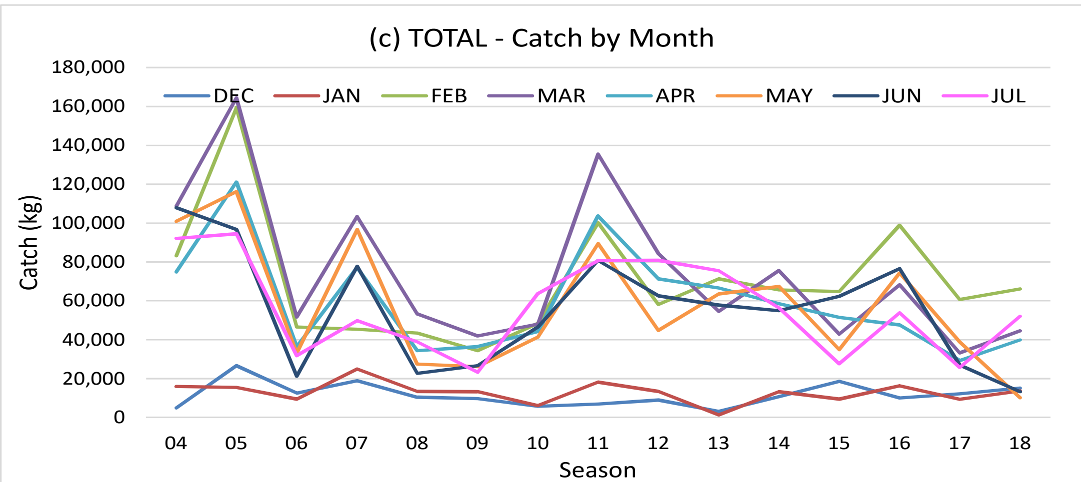



Figure 4. Map of the TIB fishing areas described in the analysis.

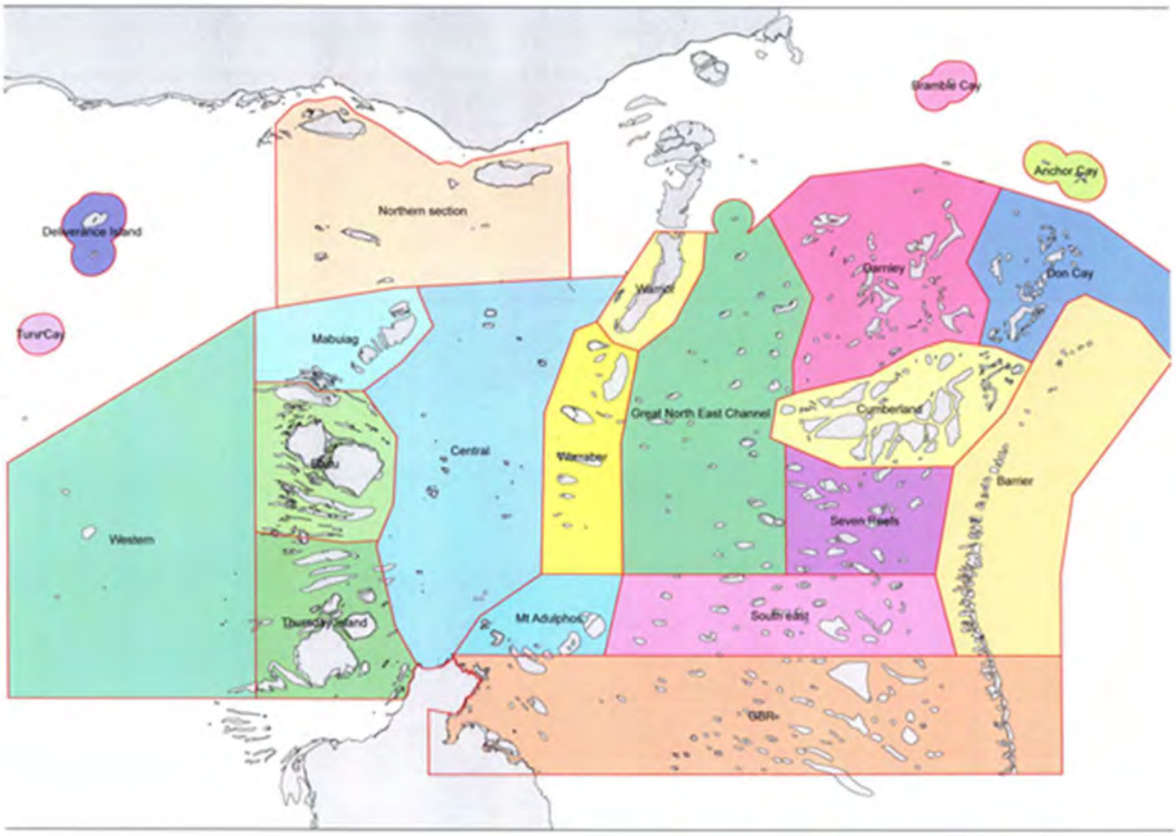



Table 2. (a) List of the area codes and names used in the TIB fishery together with the total number of data records associated with each area. A revised listing of area codes and names based on aggregating areas with few data records is shown in (b).

| Area-Name | Area | Area-Rev | N-Records |
|---|---|---|---|
| Unknown | 0 | 0 | 4,477 |
| Turu Cay | 1 | 6 | 249 |
| Deliverance Island | 2 | 6 | 29 |
| Northern Section | 3 | 6 | 269 |
| Bramble Cay | 4 | 16 | 19 |
| Anchor Cay | 5 | 16 | 9 |
| Western | 6 | 6 | 21 |
| Mabuiag | 7 | 7 | 6,181 |
| Badu | 8 | 8 | 5,915 |
| Thursday Island | 9 | 9 | 21,827 |
| Central | 10 | 10 | 763 |
| Warrior | 11 | 11 | 3,157 |
| Warraber | 12 | 12 | 4,319 |
| Mt Adolphus | 13 | 13 | 698 |
| Great NE Channel | 14 | 14 | 2,041 |
| South East | 15 | 15 | 118 |
| Darnley | 16 | 16 | 1,269 |
| Cumberland | 17 | 17 | 819 |
| Seven Reefs | 18 | 15 | 8 |
| Don Cay | 19 | 16 | 7 |
| Barrier | 20 | 15 | 10 |
| GBR | 21 | 15 | 155 |
| | | Total | 52,360 |

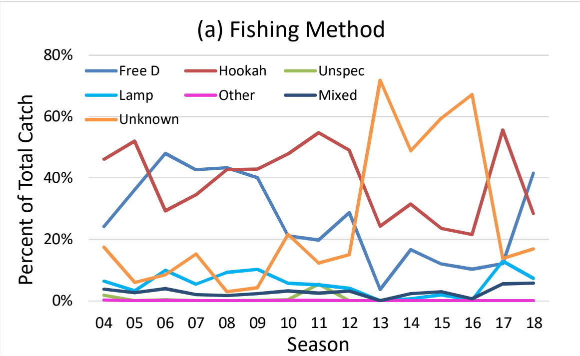
| Area-Name | Area-Rev | N-Records |
|---|---|---|
| Unknown | 0 | 4,477 |
| North-Western | 6 | 568 |
| Mabuiag | 7 | 6,181 |
| Badu | 8 | 5,915 |
| Thursday Island | 9 | 21,827 |
| Central | 10 | 763 |
| Warrior | 11 | 3,157 |
| Warraber | 12 | 4,319 |
| Mt Adolphus | 13 | 698 |
| Great NE Channel | 14 | 2,041 |
| GBR/South-east | 15 | 291 |
| Darnley | 16 | 1,304 |
| Cumberland | 17 | 819 |
| | Total | 52,360 |

## 4. TIB Sector Summary

The 21 areas used to record the spatial location of catch taken in the TIB sector are shown in Figure 4 and listed in Table 2(a). The total number of data records associated with each area for the 2004-2018 seasons is also shown. For the purpose of the following analyses, several areas where the data coverage was low were combined. A revised listing of area codes and names based on aggregating some areas is shown in Table 2(b). These are the areas and names referred to in the following Figures.

A comparison of the percent of the total TIB catch within each fishing season by (a) fishing method and (b) processed form is shown in Figure 5 while a comparison by area fished is shown in Figure 6. Note these results are based on all data available for each season, i.e. they are not limited to the temporal period (December-July) covered by the data for the 2018 season. Also note that some concerns were expressed at the RAG meeting held in May 2018 that the area-fished recorded on the TDB02 logbook may not coincide with the area where the actual fishing took place (it may instead coincide where the lobsters were sold). As such, the reader is reminded that the area-fished associated with catches in the TIB-sector may not be correct.

Figure 5. Time-series of percent of the total TIB catch within each fishing season by (a) fishing method and (b) processed form.



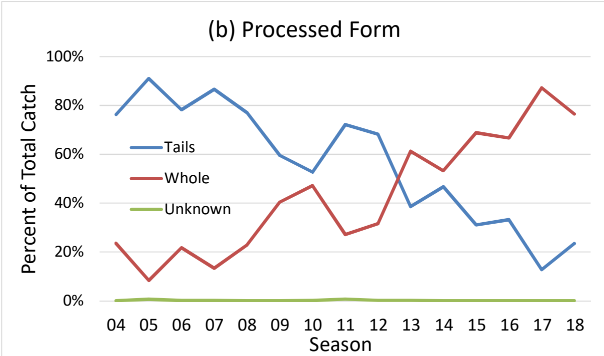




Figure 6. Time-series of percent of the total TIB catch within each fishing season taken in each area fished (as recorded on the TDB01 and TDB02 docket-books).

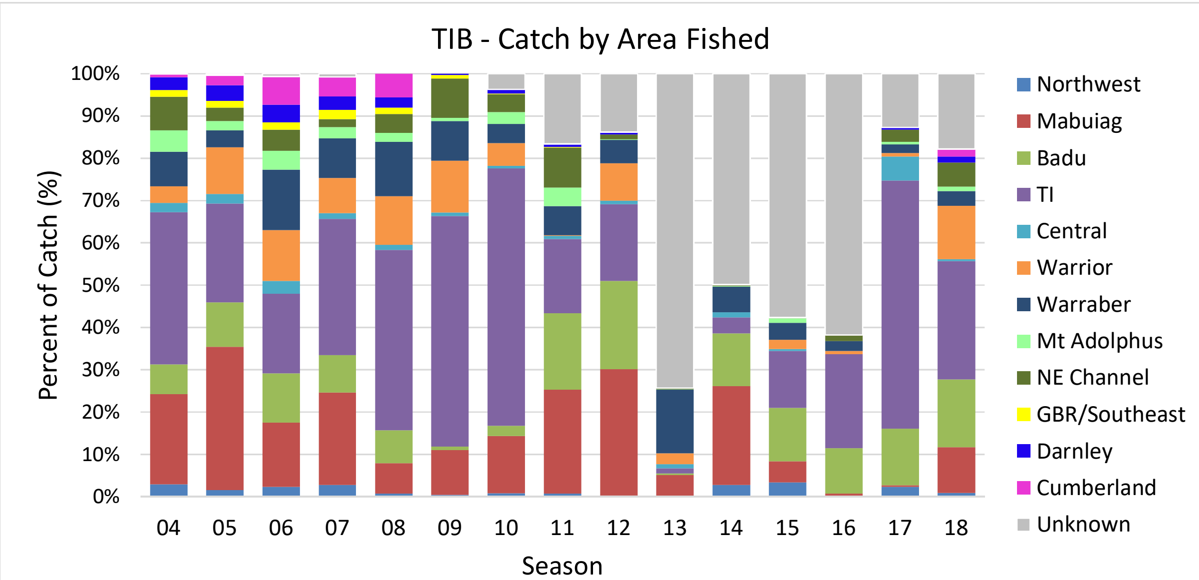
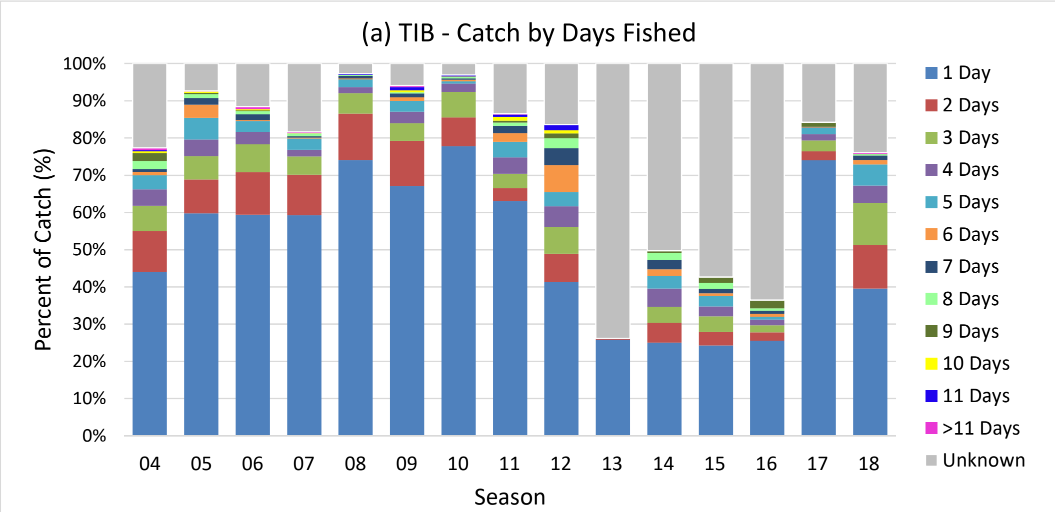


Figure 7. Comparison of percent of the TIB total annual catch stratified by the number of days fished per trip based on (a) all records including those where the days fished is unknown, and (b) those records where the unknown days fished are excluded.



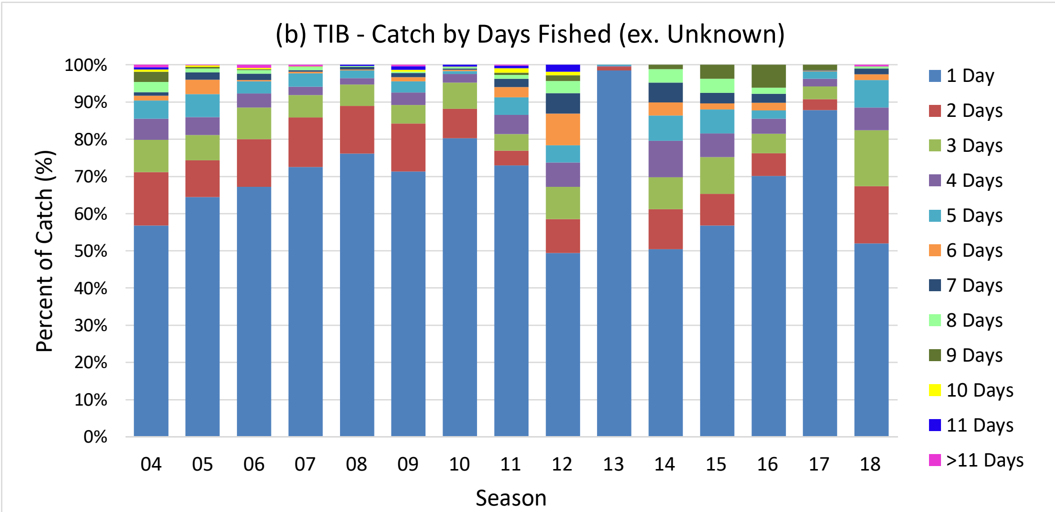
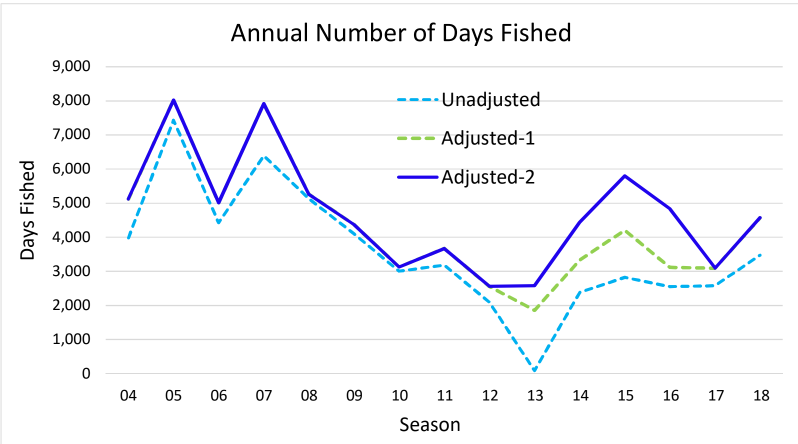




Figure 8. Seasonal comparison of estimated effort in the TIB fishery during the eight month period December-July. Analysis based on the method outlined in Campbell (2017).



A comparison of percent of the TIB total annual catch stratified by the number of days fished per trip is shown in Figure 7. As the number of days fished was not recorded for all docket-book records, and was also not available for the TIB catch provided in aggregate form by several processes, the proportion of the catch where the days fished is unknown is included in the result shown in Figure 7a. If one assumes that the distribution of days fished associated with the catch for which the effort information remains unknown is the same as that associated with the catch for which the effort information is known, then one can ascertain an estimate of the effort distribution across the entire catch by just excluding that portion of the catch where the effort information remain unknown. This result is shown in Figure 7b and indicates an increase in the proportion of the catch associated with trips of length greater than 1 day during the 2018 season. Finally, a seasonal comparison of estimated effort in the TIB fishery during the eight month period December-July is shown in Figure 8 This estimate is based on the method outlined in Campbell (2017) and uses as the total catch during these eight months those estimates shown in Table 1.

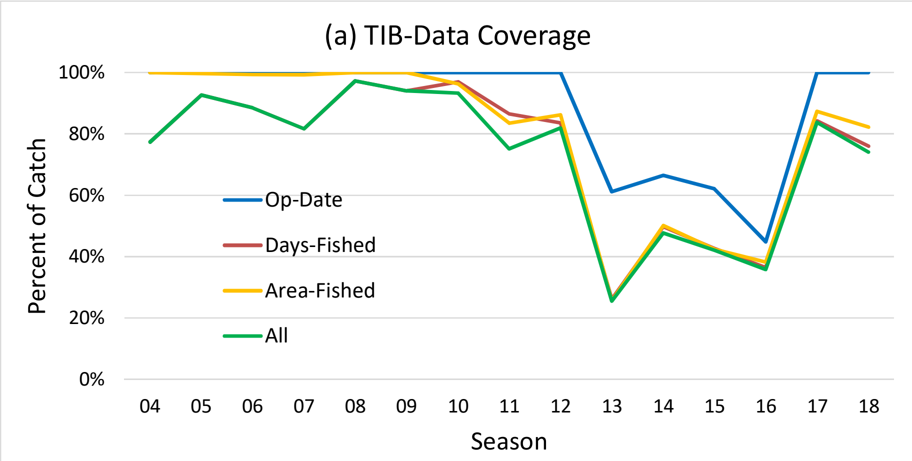
As noted above, not all the data fields on either the TBD01 or TDB02 logbooks are complete due to the voluntary nature of the provision of this information on both books. As noted above the incompleteness of these data fields creates problems in providing a complete analysis of the information for the TIB sector. An indication of availability of information is shown in Figure 9, which provides the annual percentage of the total TIB catch associated with records where various data fields are non-null. The data fields are, (i) Trip operation-date, (ii) Number of days fished, (iii) Area fished, (iv) Vessel-symbol and (v) Seller-name.

Another issue noted in previous analyses of the TIB data is the observation that while the structure of the Docket-Book would seem to indicate that there should be a unique Record-Number (Record-No) associated with each vessel, date and seller-name this structure is not strictly adhered to in the data. While analysis indicates that there is a single date, vessel and seller-name associated with each Record-No, further investigation also indicates that there are often multiple Record-Nos associated for a given vessel, date and seller-name. While the reason for these multiple records remains uncertain (they could be recording errors), in order to identity an appropriate data structure the following two sets of data were prepared for analysis:

First, the multiple Record-Nos associated for a given vessel, date and seller-name were assumed to be due to the recording of an incorrect date. As such the TIB data was aggregated by Record-No, which were each assumed to be associated with a unique record of sale for a given vessel, date and seller. Where the vessel or seller was not recorded, these fields were set to ‘Unknown’. Records were not retained where the Days-Fished was unknown, and those records associated with TIB data recorded in the TVH logbook were also eliminated as the structure of the data for these records are different. In the following this data-set is known as the By-Rec data.

Second, the TIB data was aggregated over vessel-symbol, date and seller-name and any resulting data rows associated with more than one Record-No were eliminated. Again, where the vessel-symbol or seller-name was null these fields were set to ‘Unknown’. Data where either the number of Days-Fished or the Area-Fished was not recorded, the record pertained to the TVH logbook, or the weight of the catch was zero or greater than 1000 kg were eliminated. Finally, only those data where the first fishing method listed was either ‘Hookah diving’ or ‘Free diving’ or ‘Lamp fishing’ were retained. In the following this data-set is known as the

Figure 9. Time-series of the percent of the total seasonal TIB catch associated with data records where various data fields are non-null. (a) Trip operation-date, number of days fished, area fished and all three together, and (b) vessel-symbol and seller-name.



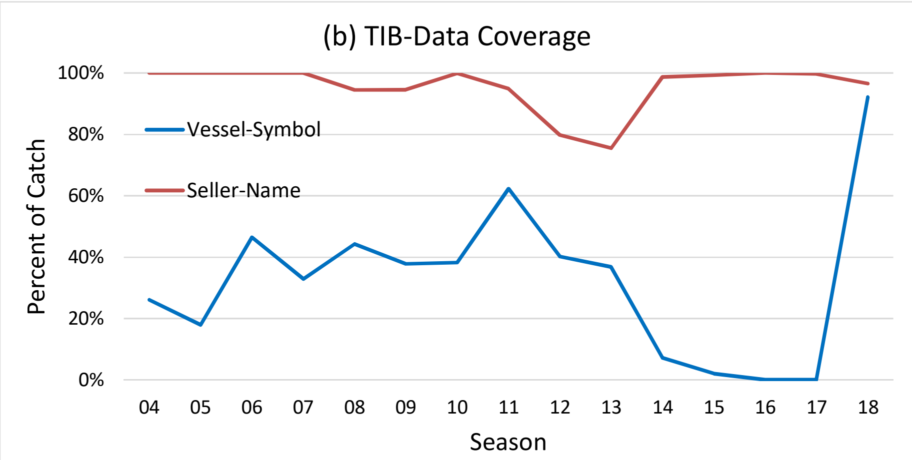
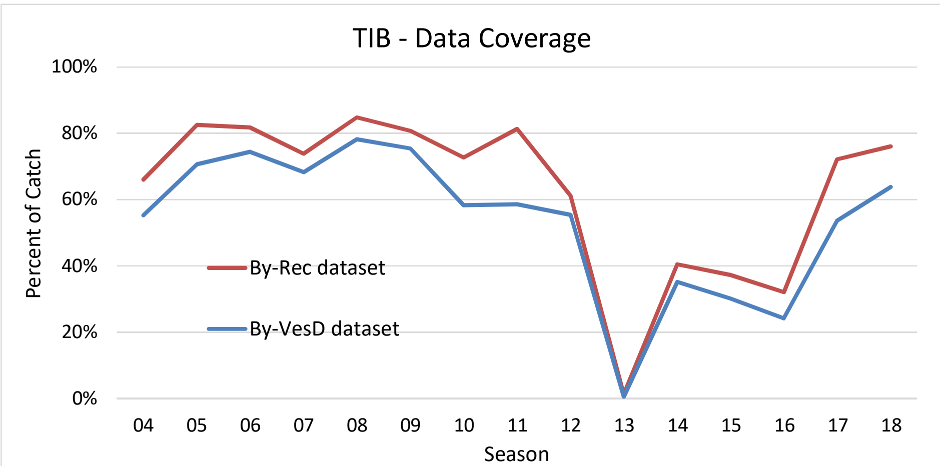




Figure 10. Time-series of the percent of the total TIB catch for the eight month period from December-to-July associated with data records included in the (a) By-Rec dataset and (b) By-VesD dataset.

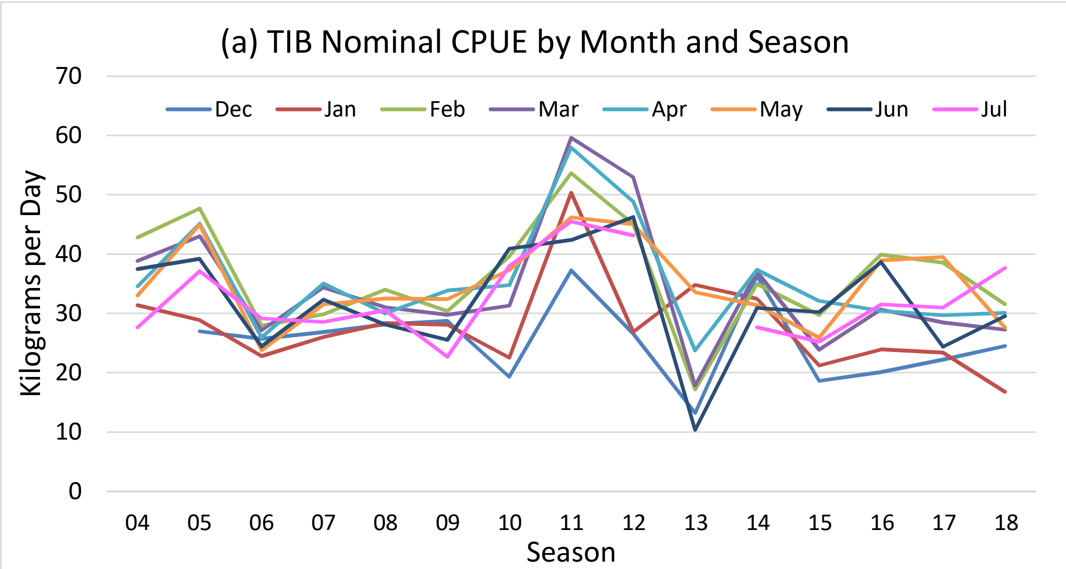


By-VesD data and is equivalent to the data sets used in previous GLM-analyses of the TIB-data.

The total number of data records pertaining to the eight month period December-to-July and over the 2004-to-2018 seasons was 40,068 and 34,814 for the By-Rec and By-VesD datasets respectively, while the respective coverage of the seasonal catch for these months by each data set is shown in Figure 10.

Using these two data sets, a series of analyses were undertaken to compare the nominal catch-rates (CPUE) according to various data stratifications. These results are shown on Figures 11 and 12. A comparison of the nominal CPUE within each area fished based on both data sets is shown in Figure 13.

Figure 11. Annual time-series of nominal CPUE for the TIB fleet within (a) month and (b) by fishing method during the eight month period December-July. Based on the By-Rec data set.



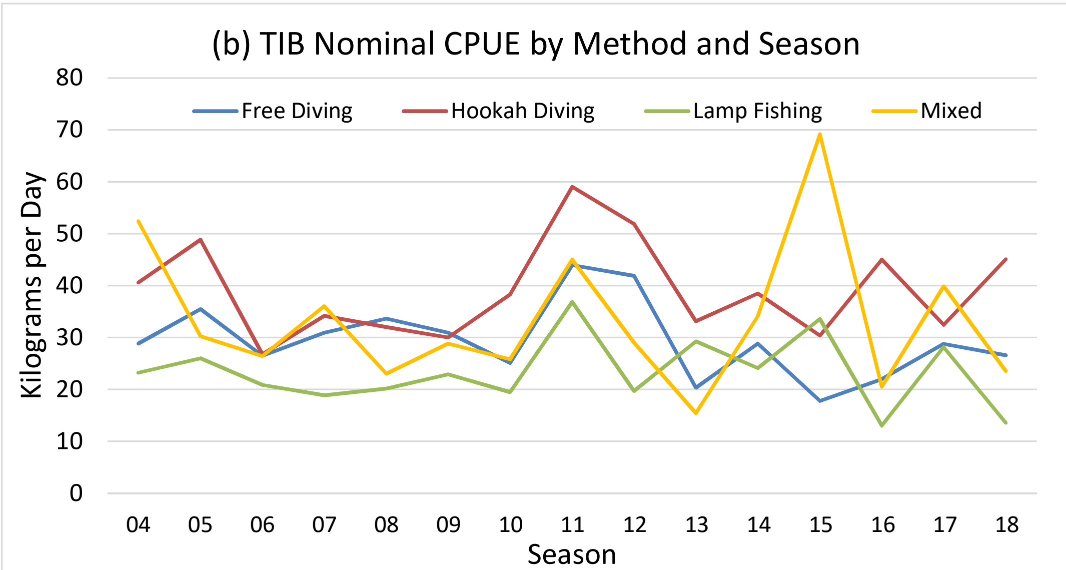
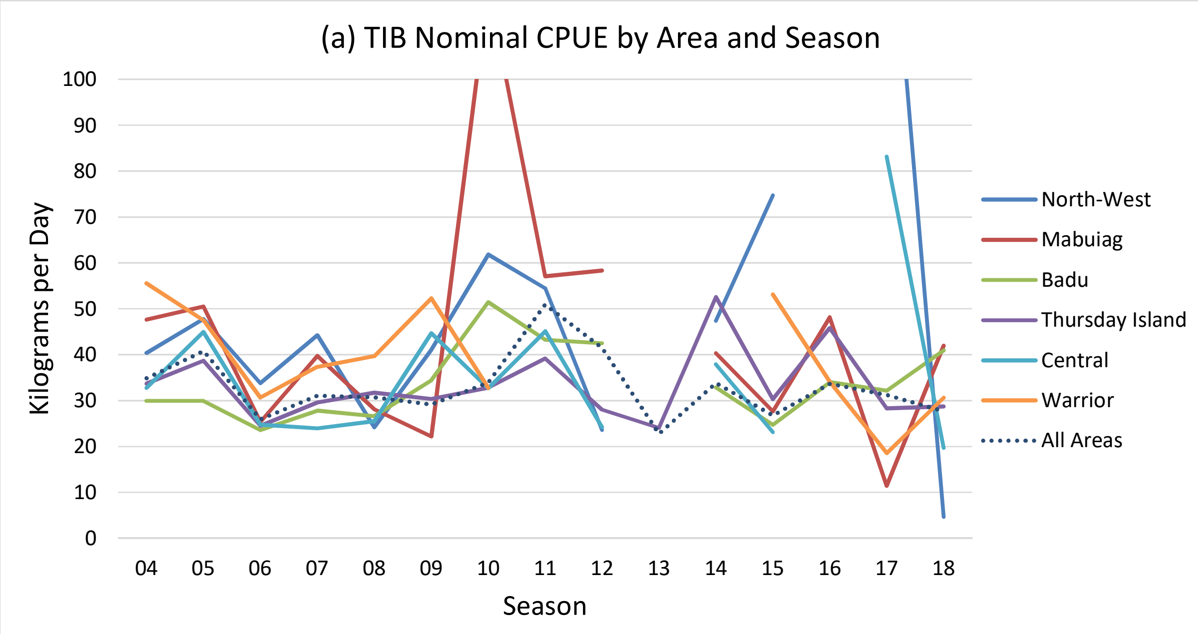



Figure 12. Annual time-series of nominal CPUE for the TIB fleet within each area fished during the eight month period December-July. For comparison, the mean nominal CPUE across all areas is also shown. Based on the By-Rec data set. Note, results are only shown for seasons and areas where five or more data records are available. Also, the reader is reminded that the area-fished associated with catches in the TIB-sector may not be correct.



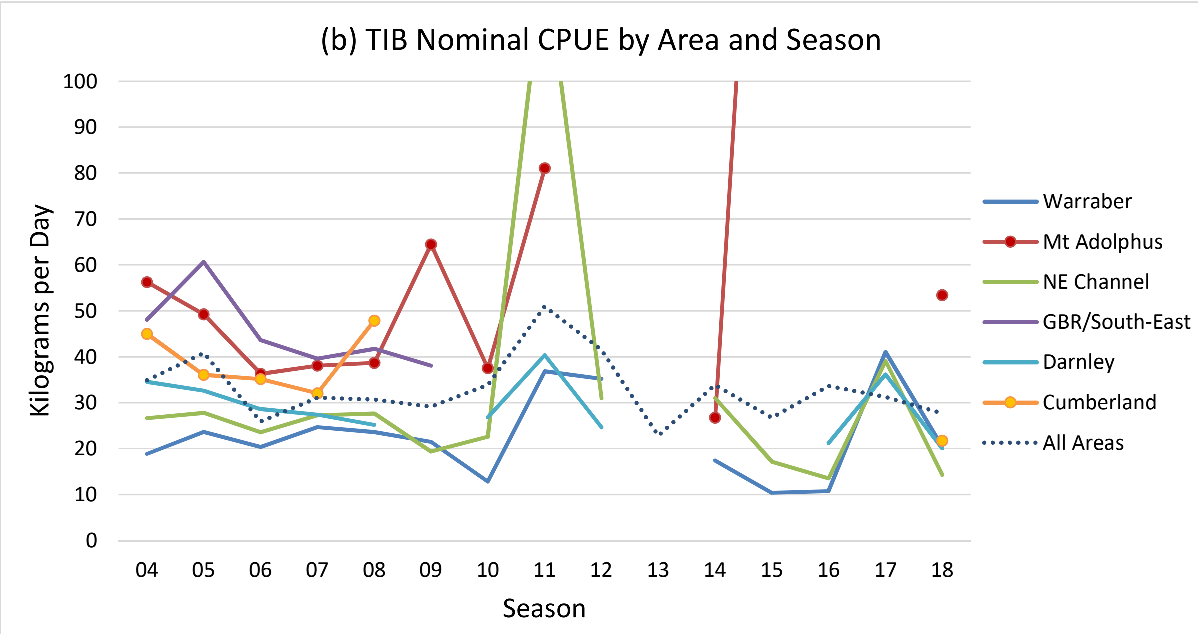



Figure 13. Comparison of the nominal TIB CPUE within each area fished (shown in Figure 12) based on both the By-Rec data set and the By-VesD data. For each area the mean CPUE across all seasons is also shown. For the 2018 season catch rates have been above the long term average in 3 areas, below the average in 8 areas, and there was no data in 1 area (GBR/Southeast). Note, results are only shown for seasons and areas where five or more data records are available. Also, the reader is reminded that the area-fished associated with catches in the TIB-sector may not be correct.


## 5. TVH Sector Summary

As for the TIB-sector, a series of analyses were undertaken of the catch and effort data for the TVH-sector to provide a comparison of fishery indicators for the 2018 season and previous seasons. As the TVH data is not plagued by the same level of non-reporting of information associated with many of the data fields note in the TIB-data (e.g. the fishing date is known for all catches in the TVH data) the analyses were able to be more focused on the six-month period between February and July each year. The results of these analyses are shown in Figures 14-22. The captions above each Figure should hopefully provide sufficient information to help the reader adequately interpret each result. Note, the TRL04 logbook limits the reporting of catch and effort to a single location, generally the location where the primary boat is anchored and not the location where tenders are actually fishing (which can range as far as 20 nm from the primary boat).

Figure 14. Annual time-series of the percent of the total TVH catch during the six month period February-July stratified by (a) fishing method and (b) process form.

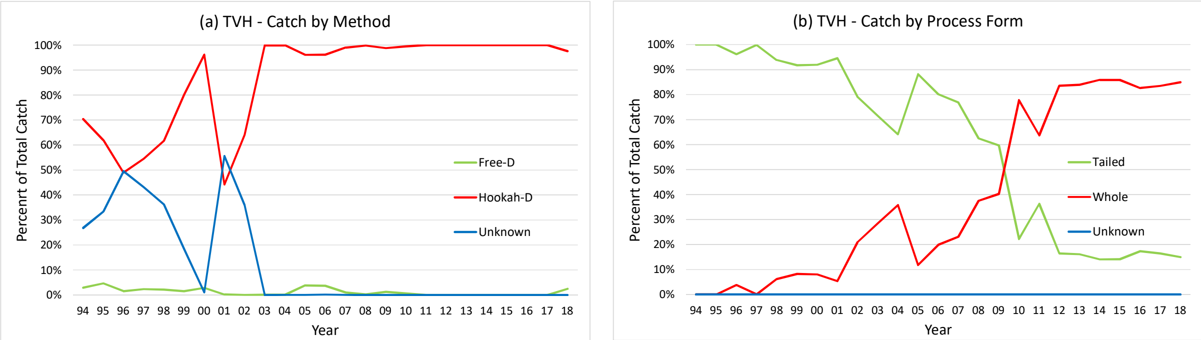



Figure 15. Annual time-series of percent of the total TVH effort (total hours fished by tenders) during the six month period February-July within each area fished. Note, this result is based only on those logbook data where effort has been recorded. The percent of the total TVH catch each year for which effort is not recorded is shown in the bottom figure. Note, during 2018 47% of total effort has been in the Northern area, 18% in the Warrior area, 15% in the Mabuiag area, and 12% in the Warraber area.

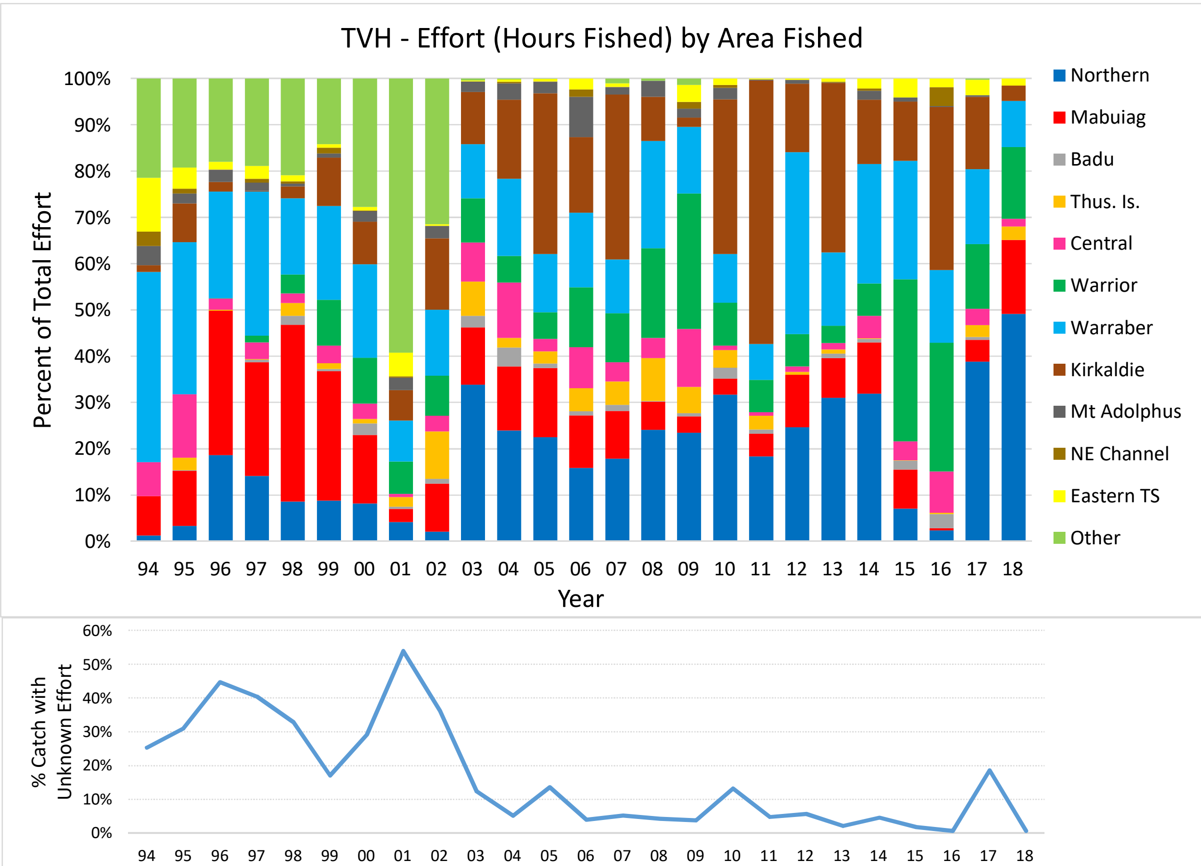


Figure 16. Map of the TVH fishing areas described in the analysis.

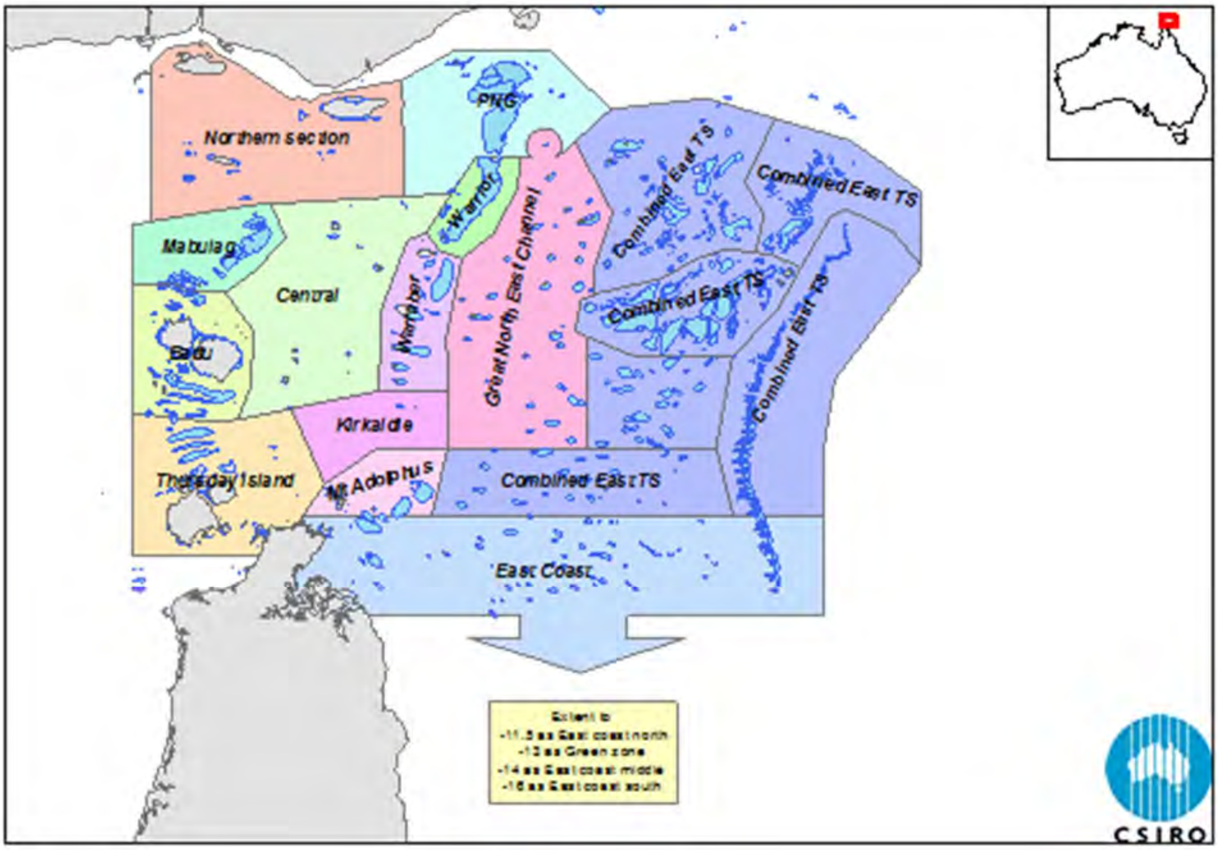



Figure 17. Annual time-series of percent of the total TVH catch during the six month period February-July taken within each area fished. Refer to Figure 16 for location of TVH areas. Note, during 2018 47% of total catch has been in the Northern area and 18% in Warrior.

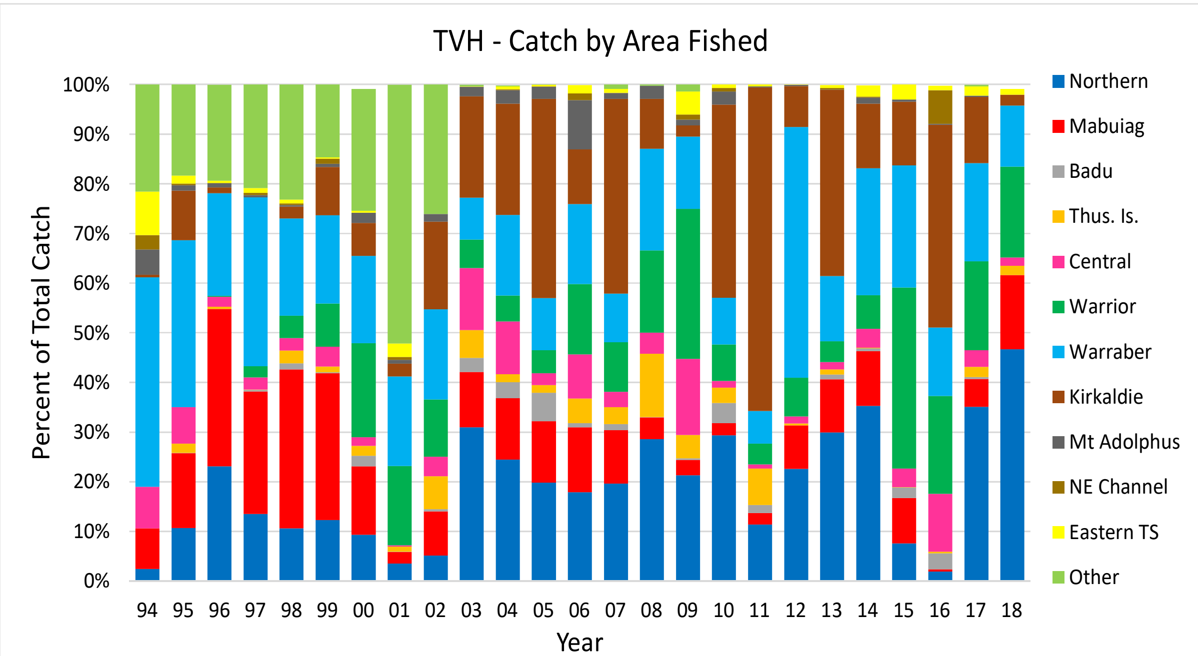
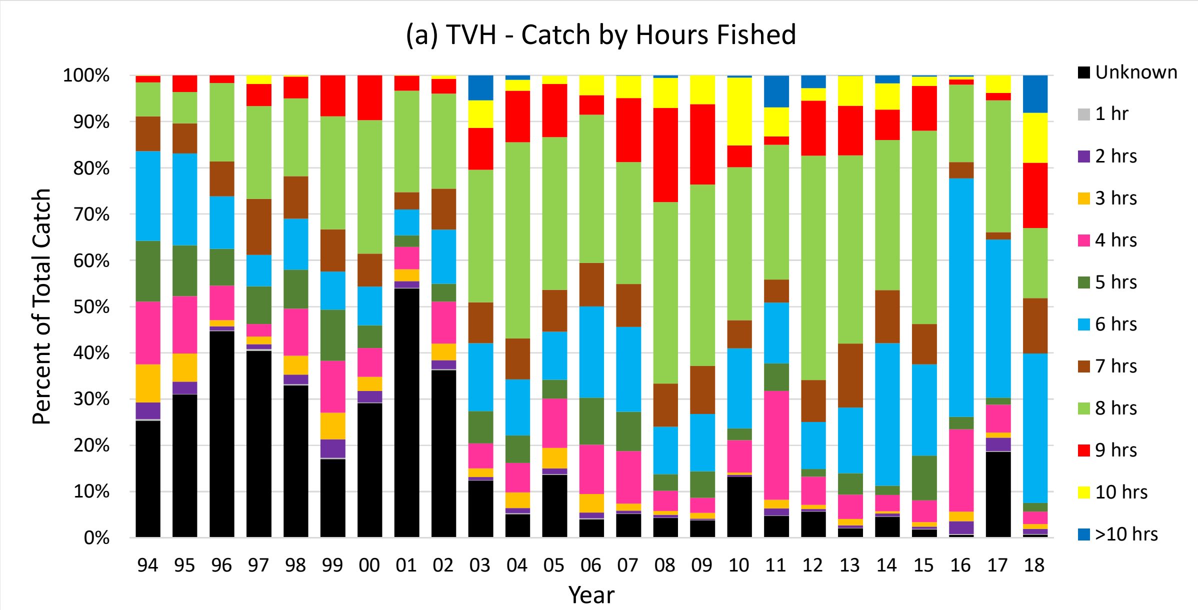


Figure 18. Comparison of percent of the TVH total catch in the six month period February-July stratified by the number of hours fished per tender-day based on (a) all records, including those where the hours fished is unknown, and (b) those records where the unknown days fished are excluded and the number of hours fished is limited to 1-9. Note, compared to the previous two years, during 2018 a higher proportion of the catch has been taken on sets with effort of more than 6 hours.



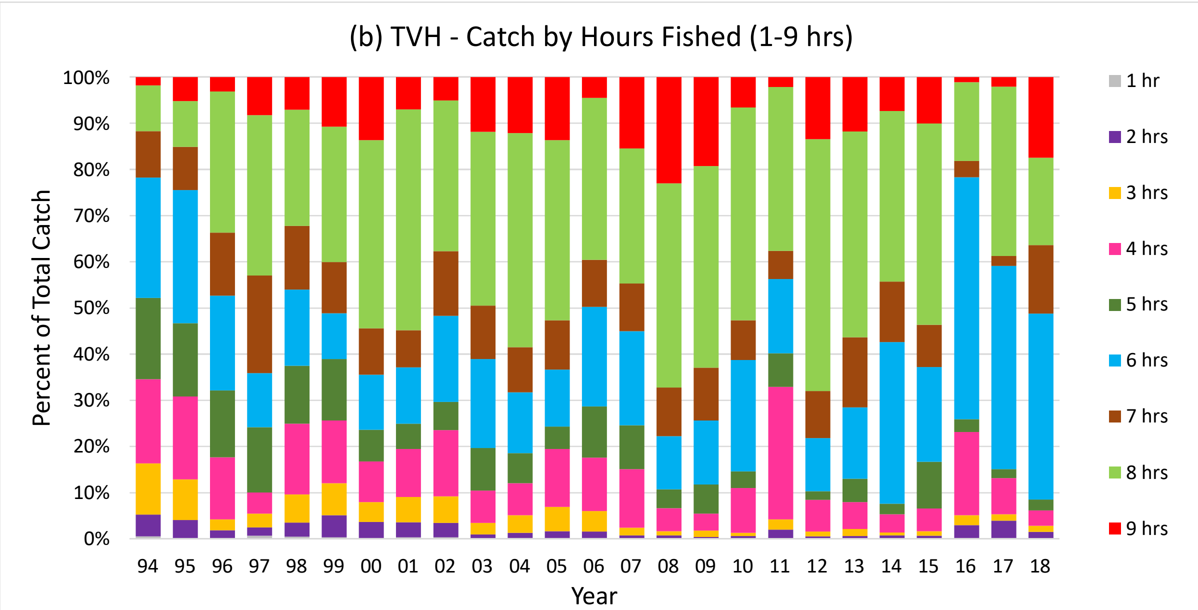
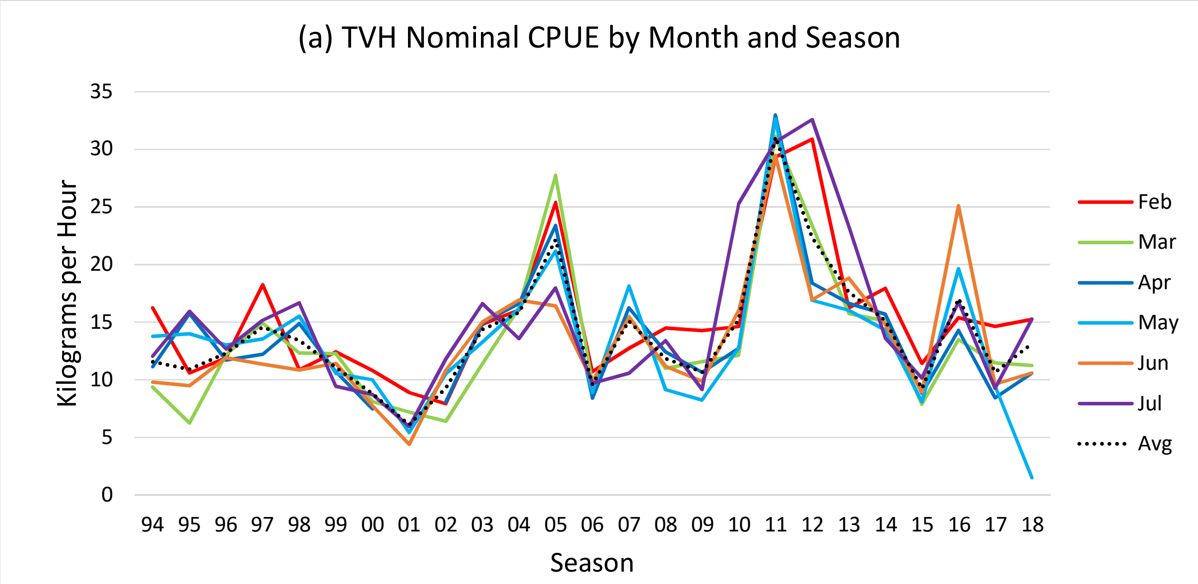



Figure 19. Annual time-series of nominal CPUE (kilograms per hour) for the TVH fleet within (a) month and (b) by fishing method during the six month period February-July. Note, generally CPUE decreases after February and in 2018 was similar in March, April and June. In 2018, the mean CPUE in March and April was 28.4% lower than in February (whereas the average decrease over the previous 6 years between 2012 and 2017 was 7.6%). Note, very little TVH fishing took place in May 2018.



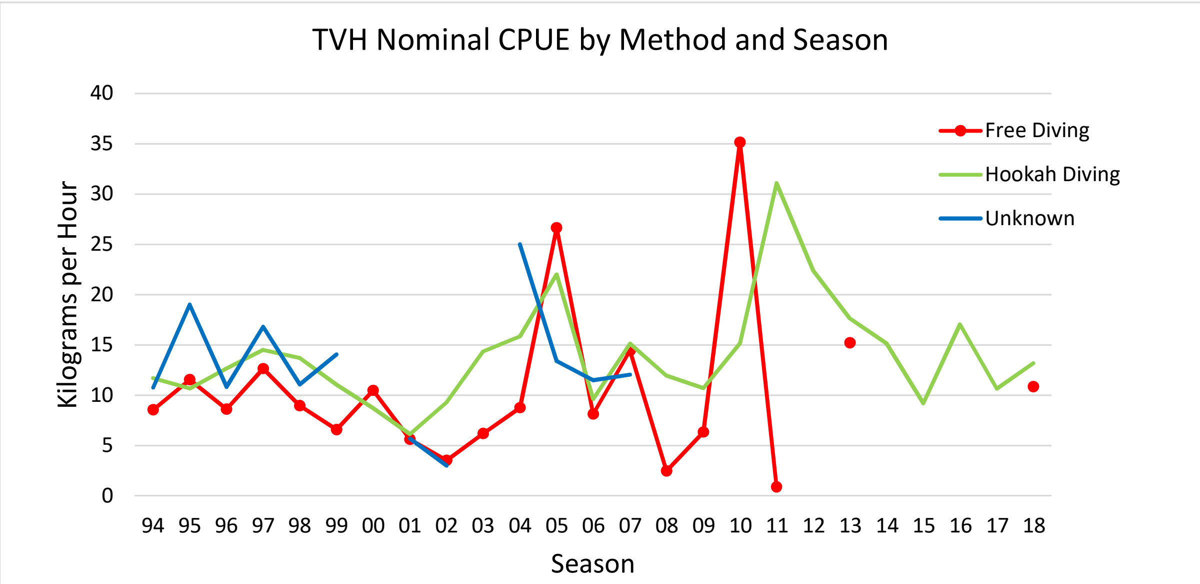
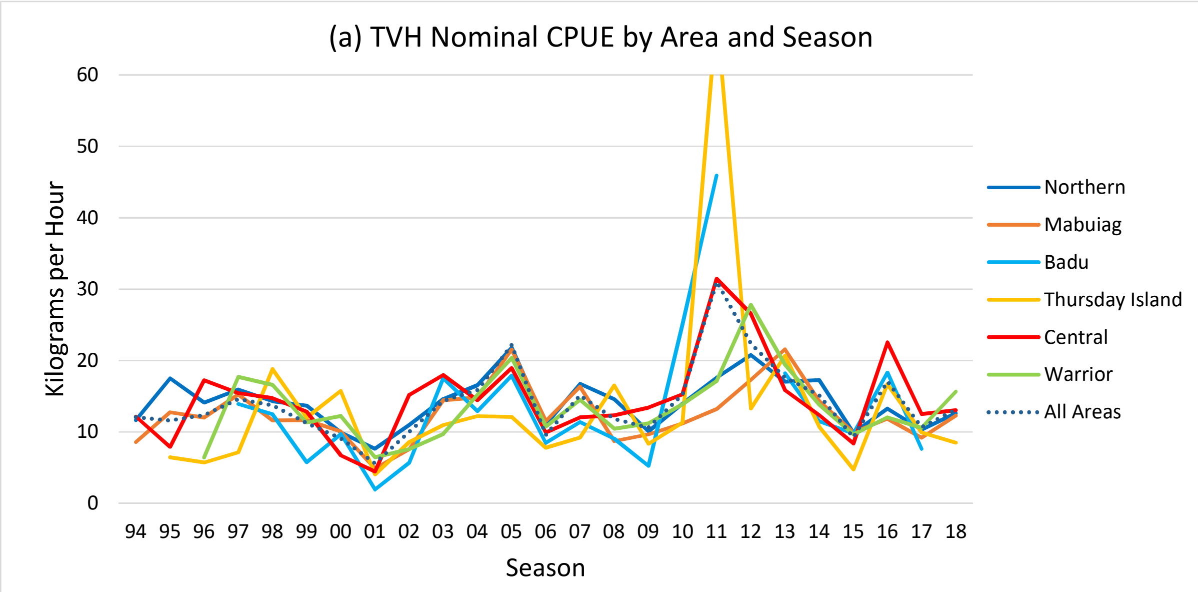



Figure 20. Annual time-series of nominal CPUE (kilograms per hour) for the TVH fleet within each area fished during the six month period February-July. For comparison, the mean nominal CPUE across all areas is also shown. Note, across all areas the mean CPUE in 2018 of 13.1 is lower than the mean catch rates over the previous 6 years (15.4), though slightly higher than in 2017 (10.7).



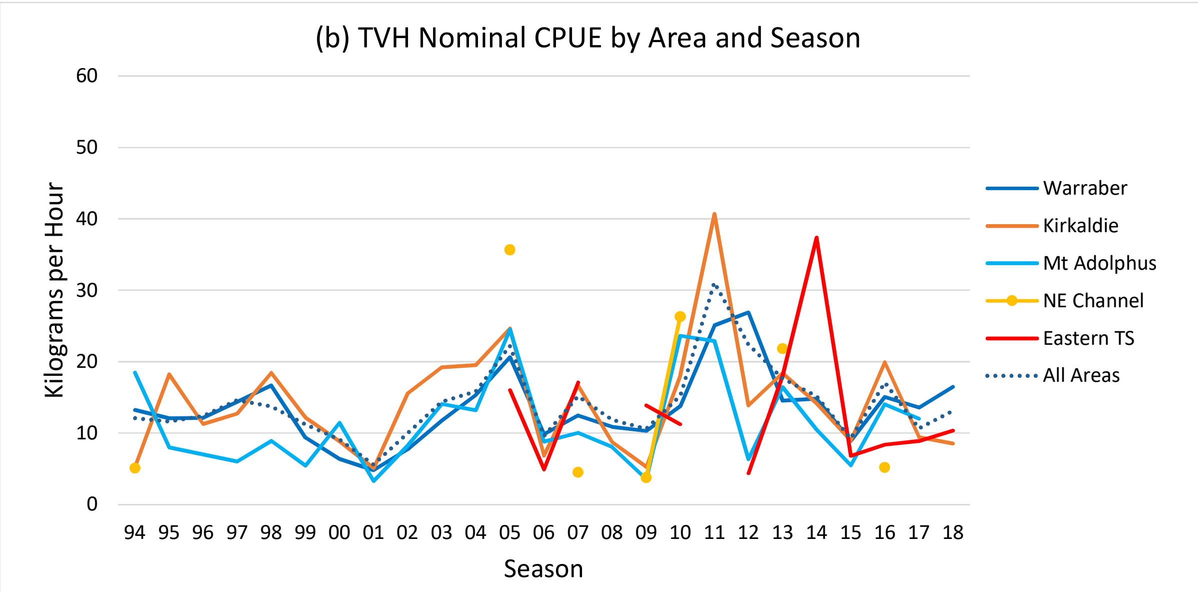



Figure 21. Annual comparison of effort in the TVH fishery during the six month period February-July. Analysis based on the method outlined in Campbell (2017).

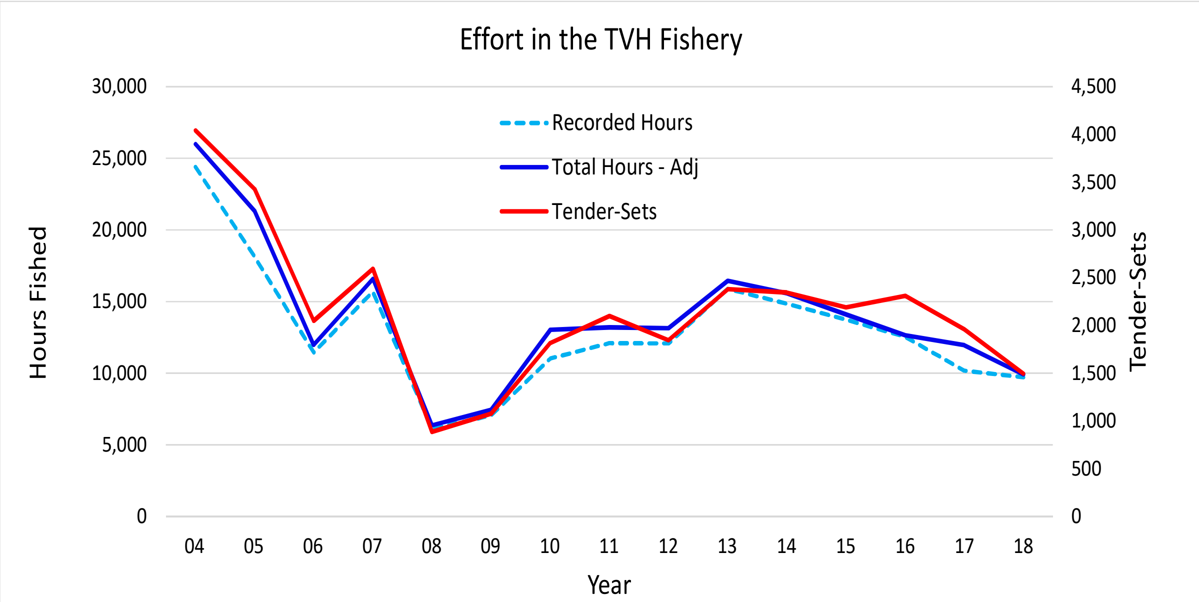
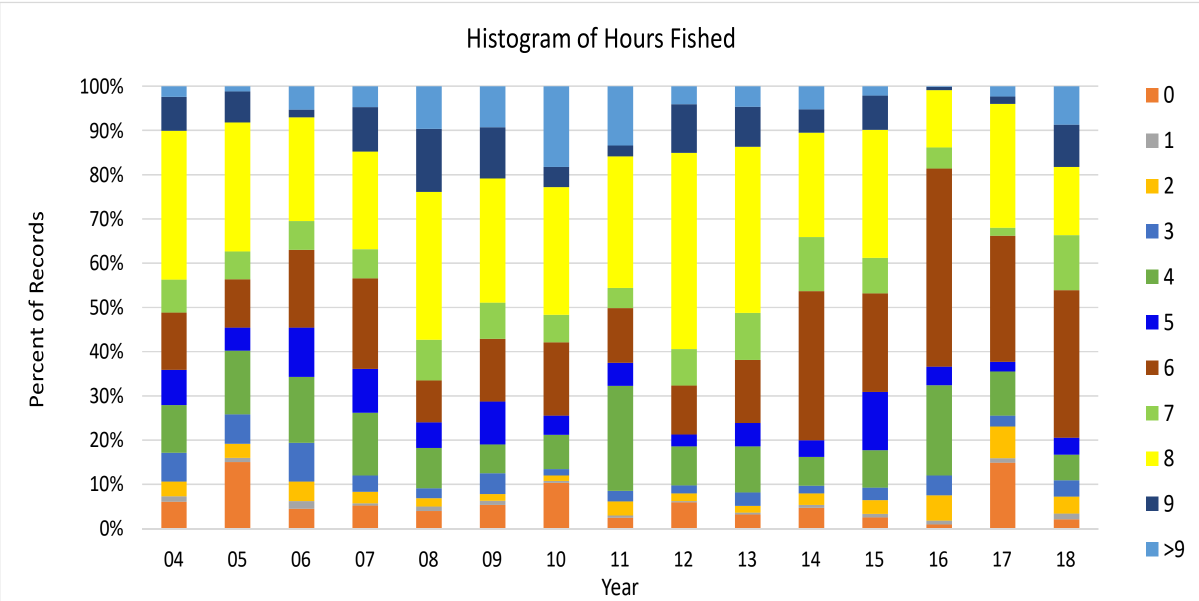



Figure 22. Annual comparison of the histogram of the number of hours fished per tender-day for the entire TVH fleet during the six month period February-July. Note, data where the hours fished was not reported have been excluded.



**References.**

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Campbell, R.A. Plaganyi, E, Deng, R., 2017a. Use of TIB Docket-Book Data to construct an Annual Abundance Index for Torres Strait Rock Lobster – 2017 update. Information paper presented to the 21st meeting of the Torres Strait Rock Lobster Resource Assessment Group, held 12-13 December 2017, Cairns.

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# Use of TVH Logbook Data to construct an Annual Abundance Index for Torres Strait Rock Lobster – 2018 Update

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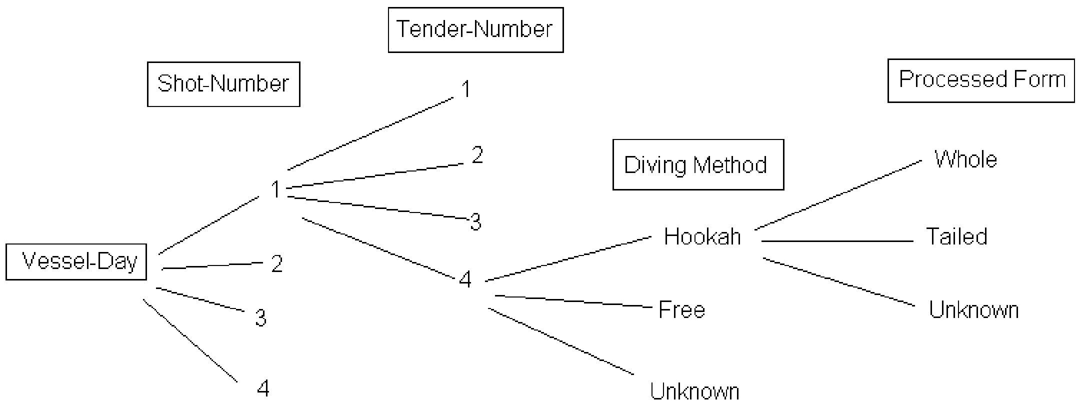
CSIRO Oceans and Atmosphere Flagship

October 2018

## 1. TVH Data

The Torres Strait Tropical Rock Lobster Fishery Daily Fishing Log (TRL04) is used to record the catches taken in the TVH sector of the Torres Strait rock lobster fishery. Logbook data obtained from AFMA consists of 99,267 individual catch records for the TVH rock-lobster fishery for the 25 years from 1994 to 2018. The structure of the data is shown in Figure 1. For each vessel-day there can be multiple shots (up to 4) with each shot consisting of up to 8 tenders. Each tender has a catch recorded by diving method (hookah, free or unknown) and the catch is recorded by processed form (whole, tailed or unknown). The data was aggregated so that each record refers to the catch for a unique vessel-day, shot, tender and diving method. This gave 70,283 records.

Figure 1. Structure of the TVH data




The distribution of these 70,283 catch records by year and month, diving method, processed state of catch and MSE-area are given in Tables 1-3. There has been little if any effort during October and November before 2006 and since 2006 there has been little effort in the months October-to-January. As such the analysis was limited to the 8 months between February and September. Similarly the analysis was also limited to those records with a known MSE-area (i.e. areas designated A0 and A99 were excluded) though areas 201 and 202 were combined (to provide a better data coverage, and designated as area 110) and area 401 (GBR) was also excluded.

In the past CPUE has been recorded as the catch-per-tender-set. However, as there can be multiple shots-per-day the duration of a tender-set can obviously vary and each tender-set cannot be assumed to be equivalent to a tender-day. The catch data also contains a field "Hours-Fished" which records the duration of the fishing trip for each tender-set and this was deemed to be a better measure of tender effort than assuming

## Table 1. Number of TVH catch records by year and month.

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1994 | 84 | 105 | 236 | 448 | 347 | 364 | 227 | 310 | 270 | | | 54 | 2445 |
| 1995 | 23 | 116 | 123 | 147 | 185 | 220 | 121 | 239 | 238 | 3 | | 220 | 1635 |
| 1996 | 366 | 237 | 447 | 247 | 378 | 264 | 356 | 517 | 411 | | | 324 | 3547 |
| 1997 | 383 | 232 | 307 | 239 | 598 | 333 | 438 | 538 | 327 | 18 | | 598 | 4011 |
| 1998 | 445 | 739 | 551 | 484 | 486 | 587 | 553 | 603 | 493 | | 9 | 231 | 5181 |
| 1999 | 117 | 98 | 262 | 242 | 208 | 214 | 161 | 132 | 146 | | | 235 | 1815 |
| 2000 | 196 | 240 | 349 | 215 | 328 | 370 | 342 | 232 | 99 | | 66 | 274 | 2711 |
| 2001 | 375 | 97 | 223 | 65 | 259 | 270 | 206 | 174 | 119 | 9 | 1 | 87 | 1885 |
| 2002 | 26 | 285 | 365 | 295 | 401 | 400 | 360 | 492 | 398 | | | 89 | 3111 |
| 2003 | 100 | 461 | 488 | 393 | 490 | 518 | 527 | 596 | 413 | | | 176 | 4162 |
| 2004 | 24 | 607 | 712 | 571 | 662 | 761 | 729 | 633 | 395 | | | 106 | 5200 |
| 2005 | 13 | 662 | 615 | 543 | 519 | 538 | 552 | 533 | 323 | | | 4 | 4302 |
| 2006 | | 409 | 436 | 361 | 286 | 206 | 349 | 289 | 92 | | | | 2428 |
| 2007 | | 288 | 427 | 446 | 542 | 489 | 402 | 184 | 91 | | | | 2869 |
| 2008 | | 133 | 222 | 113 | 161 | 96 | 159 | 175 | 152 | | | | 1211 |
| 2009 | | 148 | 227 | 174 | 201 | 200 | 125 | 163 | 70 | | | | 1308 |
| 2010 | | 255 | 333 | 302 | 324 | 292 | 309 | 294 | 253 | | 6 | | 2368 |
| 2011 | | 286 | 384 | 371 | 322 | 380 | 356 | 310 | 261 | | | | 2670 |
| 2012 | | 166 | 344 | 371 | 311 | 336 | 318 | 264 | 201 | | | | 2311 |
| 2013 | | 461 | 383 | 414 | 424 | 324 | 374 | 385 | 243 | | | | 3008 |
| 2014 | | 357 | 404 | 297 | 433 | 408 | 445 | 274 | 291 | | 1 | | 2910 |
| 2015 | | 419 | 408 | 441 | 355 | 313 | 253 | 357 | 137 | | | | 2683 |
| 2016 | 12 | 500 | 444 | 315 | 379 | 349 | 323 | 191 | 141 | | | 9 | 2663 |
| 2017 | 7 | 397 | 254 | 322 | 383 | 310 | 292 | 277 | 101 | | | | 2343 |
| 2018 | 10 | 436 | 360 | 335 | 10 | 47 | 308 | | | | | | 1506 |
| Total | 2,181 | 8,134 | 9,304 | 8,151 | 8,992 | 8,589 | 8,585 | 8,162 | 5,665 | 30 | 83 | 2,407 | 70,283 |

## Table 2. Annual number of TVH catch records by diving method and TVH catch by processed state.

| | Number of Vessel by - | | | Diving Method | | | Total | Catch by Processed State (kg) | | | Total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Name | Symbol | Both# | Hookah | Free | Unknown | Records | Tails | Whole | Unknown | Catch | %Tails | %Whole |
| 1994 | 11 | 11 | 11 | 1,505 | 136 | 804 | 2,445 | 123,006 | 0 | 0 | 123,006 | 100.0% | 0.0% |
| 1995 | 14 | 14 | 14 | 947 | 59 | 629 | 1,635 | 100,407 | 635 | 0 | 101,042 | 99.4% | 0.6% |
| 1996 | 20 | 20 | 20 | 1,609 | 87 | 1,851 | 3,547 | 219,045 | 7,810 | 0 | 226,855 | 96.6% | 3.4% |
| 1997 | 20 | 20 | 20 | 1,890 | 112 | 2,009 | 4,011 | 273,151 | 1,880 | 8 | 275,040 | 99.3% | 0.7% |
| 1998 | 23 | 22 | 23 | 2,681 | 169 | 2,331 | 5,181 | 310,635 | 18,922 | 0 | 329,556 | 94.3% | 5.7% |
| 1999 | 15 | 14 | 15 | 1,412 | 38 | 365 | 1,815 | 88,416 | 6,681 | 0 | 95,097 | 93.0% | 7.0% |
| 2000 | 20 | 19 | 20 | 2,330 | 114 | 267 | 2,711 | 118,824 | 10,038 | 0 | 128,862 | 92.2% | 7.8% |
| 2001 | 14 | 14 | 14 | 812 | 26 | 1,047 | 1,885 | 66,347 | 2,729 | 0 | 69,076 | 96.0% | 4.0% |
| 2002 | 17 | 17 | 17 | 1,721 | 10 | 1,380 | 3,111 | 108,216 | 39,471 | 0 | 147,687 | 73.3% | 26.7% |
| 2003 | 21 | 21 | 21 | 3,958 | 104 | 100 | 4,162 | 255,447 | 105,964 | 0 | 361,411 | 70.7% | 29.3% |
| 2004 | 25 | 24 | 25 | 5,045 | 154 | 1 | 5,200 | 317,467 | 163,651 | 0 | 481,118 | 66.0% | 34.0% |
| 2005 | 22 | 23 | 23 | 4,101 | 199 | 2 | 4,302 | 484,497 | 60,480 | 0 | 544,977 | 88.9% | 11.1% |
| 2006 | 22 | 20 | 22 | 2,307 | 119 | 2 | 2,428 | 108,909 | 26,539 | 0 | 135,448 | 80.4% | 19.6% |
| 2007 | 20 | 20 | 20 | 2,829 | 39 | 1 | 2,869 | 207,463 | 61,133 | 0 | 268,596 | 77.2% | 22.8% |
| 2008 | 13 | 12 | 14 | 1,205 | 6 | 0 | 1,211 | 63,378 | 37,060 | 0 | 100,438 | 63.1% | 36.9% |
| 2009 | 10 | 10 | 10 | 1,281 | 27 | 0 | 1,308 | 51,322 | 39,729 | 10 | 91,061 | 56.4% | 43.6% |
| 2010 | 13 | 12 | 13 | 2,356 | 12 | 0 | 2,368 | 67,817 | 214,797 | 0 | 282,614 | 24.0% | 76.0% |
| 2011 | 14 | 13 | 14 | 2,668 | 1 | 1 | 2,670 | 171,469 | 332,064 | 0 | 503,533 | 34.1% | 65.9% |
| 2012 | 14 | 13 | 14 | 2,311 | 0 | 0 | 2,311 | 65,282 | 305,198 | 2 | 370,482 | 17.6% | 82.4% |
| 2013 | 11 | 12 | 12 | 3,006 | 2 | 0 | 3,008 | 61,631 | 300,030 | 0 | 361,661 | 17.0% | 83.0% |
| 2014 | 13 | 13 | 13 | 2,910 | 0 | 0 | 2,910 | 42,105 | 230,961 | 120 | 273,186 | 15.4% | 84.5% |
| 2015 | 13 | 12 | 13 | 2,682 | 1 | 0 | 2,683 | 22,479 | 130,231 | 0 | 152,709 | 14.7% | 85.3% |
| 2016 | 12 | 11 | 12 | 2,642 | 21 | 0 | 2,663 | 42,714 | 200,986 | 0 | 243,700 | 14.7% | 85.3% |
| 2017 | 11 | 12 | 12 | 2,340 | 3 | 0 | 2,343 | 23,885 | 125,163 | 0 | 149,048 | 14.7% | 85.3% |
| 2018 | 9 | 9 | 9 | 1,434 | 72 | 0 | 1,506 | 19,159 | 109,142 | 22 | 128,323 | 14.9% | 85.1% |
| Total | | | | 57,982 | 1,511 | 10,790 | 70,283 | 3,413,071 | 2,531,294 | 162 | 5,944,526 | 57.4% | 42.6% |

Table 3. Number of TVH catch records by MSE-area.

| | Northern | Mabuiag | Badu | Thurs Is. | Central | Warrior | Warraber | Kirkaldie | Adolphus | East TS | East TS | GBR | East Coast | NR | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YEAR | A101 | A102 | A103 | A104 | A105 | A106 | A107 | A108 | A109 | A201 | A202 | A401 | A0 | A-99 | TOTAL |
| 1994 | 51 | 257 | | 11 | 119 | | 926 | 64 | 89 | 106 | 177 | 1 | | 392 | 2445 |
| 1995 | 106 | 289 | 2 | 41 | 83 | | 487 | 111 | 26 | 36 | 32 | 4 | | 223 | 1635 |
| 1996 | 620 | 1152 | 2 | 11 | 51 | 11 | 719 | 41 | 37 | 1 | 32 | | | 608 | 3547 |
| 1997 | 425 | 1324 | 21 | 19 | 73 | 100 | 881 | 4 | 21 | 52 | 33 | 3 | 1 | 630 | 4011 |
| 1998 | 463 | 1681 | 51 | 128 | 107 | 200 | 1042 | 160 | 16 | 31 | 45 | | 2 | 794 | 5181 |
| 1999 | 158 | 457 | 34 | 33 | 66 | 177 | 348 | 177 | 17 | 14 | 30 | 15 | | 212 | 1815 |
| 2000 | 137 | 252 | 66 | 48 | 51 | 404 | 605 | 229 | 59 | 7 | 22 | 35 | | 370 | 2711 |
| 2001 | 42 | 70 | 5 | 44 | 26 | 329 | 366 | 83 | 40 | 3 | 41 | 44 | | 405 | 1885 |
| 2002 | 107 | 278 | 18 | 176 | 44 | 351 | 592 | 718 | 48 | | 17 | 16 | | 401 | 3111 |
| 2003 | 1080 | 442 | 112 | 315 | 344 | 396 | 432 | 832 | 96 | 7 | 49 | 4 | 4 | 33 | 4162 |
| 2004 | 1072 | 612 | 209 | 159 | 551 | 343 | 980 | 970 | 208 | 15 | 51 | 8 | | 9 | 5200 |
| 2005 | 803 | 466 | 161 | 194 | 156 | 211 | 511 | 1680 | 90 | 3 | 18 | 6 | | | 4302 |
| 2006 | 362 | 267 | 20 | 131 | 187 | 300 | 440 | 351 | 280 | 34 | 48 | 4 | | | 2428 |
| 2007 | 483 | 293 | 42 | 146 | 120 | 311 | 367 | 980 | 62 | 6 | 28 | 2 | | | 2869 |
| 2008 | 236 | 58 | 6 | 91 | 52 | 235 | 240 | 206 | 48 | 2 | 31 | 3 | | 2 | 1211 |
| 2009 | 268 | 46 | 5 | 80 | 145 | 365 | 231 | 47 | 26 | 23 | 59 | 7 | | | 1308 |
| 2010 | 564 | 67 | 103 | 103 | 33 | 197 | 206 | 992 | 43 | 12 | 32 | 14 | | | 2368 |
| 2011 | 389 | 111 | 34 | 83 | 17 | 159 | 430 | 1406 | 25 | | 14 | | | | 2670 |
| 2012 | 417 | 217 | | 14 | 46 | 155 | 1166 | 267 | 18 | 5 | 5 | | | | 2311 |
| 2013 | 718 | 239 | 34 | 16 | 63 | 168 | 469 | 1267 | 6 | 6 | 21 | | | | 3008 |
| 2014 | 777 | 263 | 15 | 27 | 165 | 268 | 786 | 445 | 47 | 14 | 93 | | | | 2910 |
| 2015 | 176 | 173 | 45 | 5 | 117 | 874 | 661 | 486 | 25 | | 121 | | | | 2683 |
| 2016 | 66 | 12 | 62 | 7 | 202 | 681 | 454 | 950 | 18 | 131 | 60 | | | | 2663 |
| 2017 | 726 | 108 | 9 | 43 | 67 | 401 | 461 | 422 | 15 | | 74 | | | | 2343 |
| 2018 | 735 | 218 | | 34 | 32 | 233 | 164 | 55 | | | 22 | | | | 1506 |
| Total | 10,981 | 9,352 | 1,056 | 1,959 | 2,917 | 6,869 | 13,964 | 12,943 | 1,360 | 508 | 1,155 | 166 | 7 | 4,079 | 70,283 |

Figure 2. The total number of TVH catch records each year and the number of records for which the corresponding effort data is available. The percentage of records for which no effort is recorded is also shown (right hand axis).

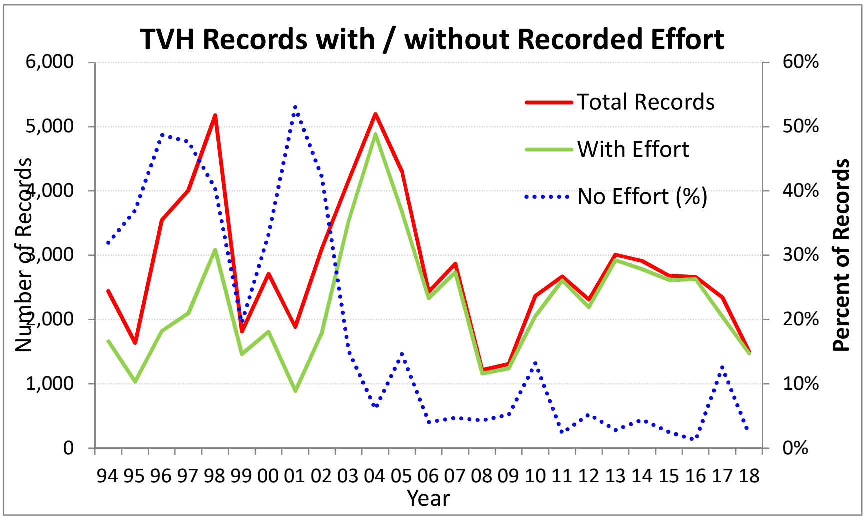



Figure 3. The percent of total TVH catch each year (a) caught by each fishing method, and (b) landed as Tails or Whole weight.

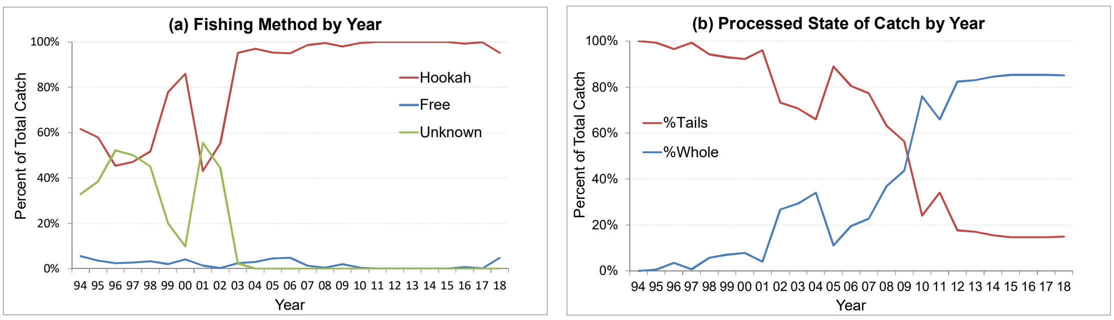
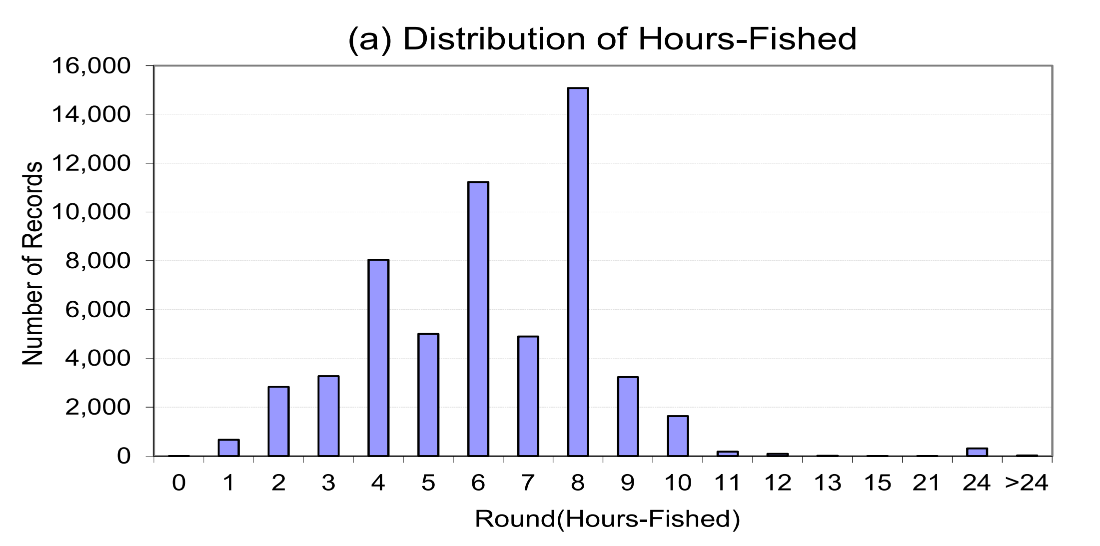
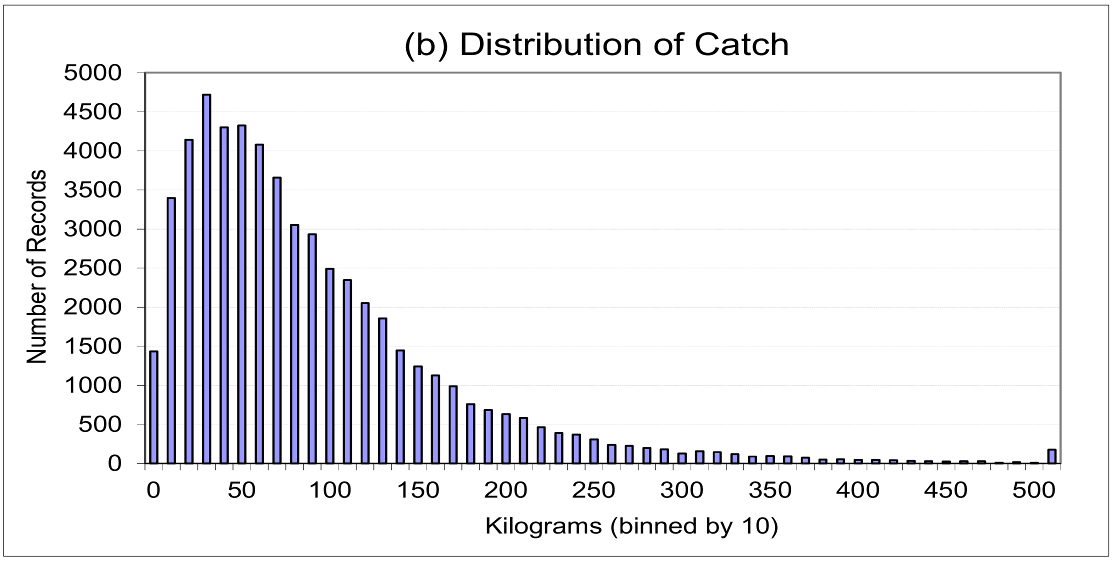


Figure 4. Distribution of (a) effort, (b) catch and (c) CPUE for the 56,534 records for which effort was recorded on TVH logbooks.



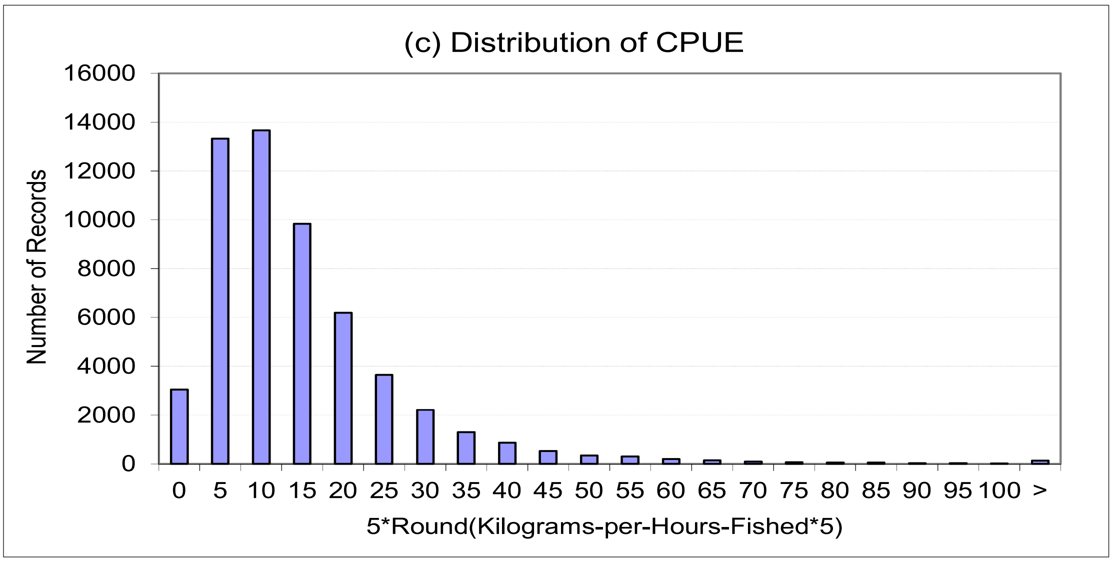
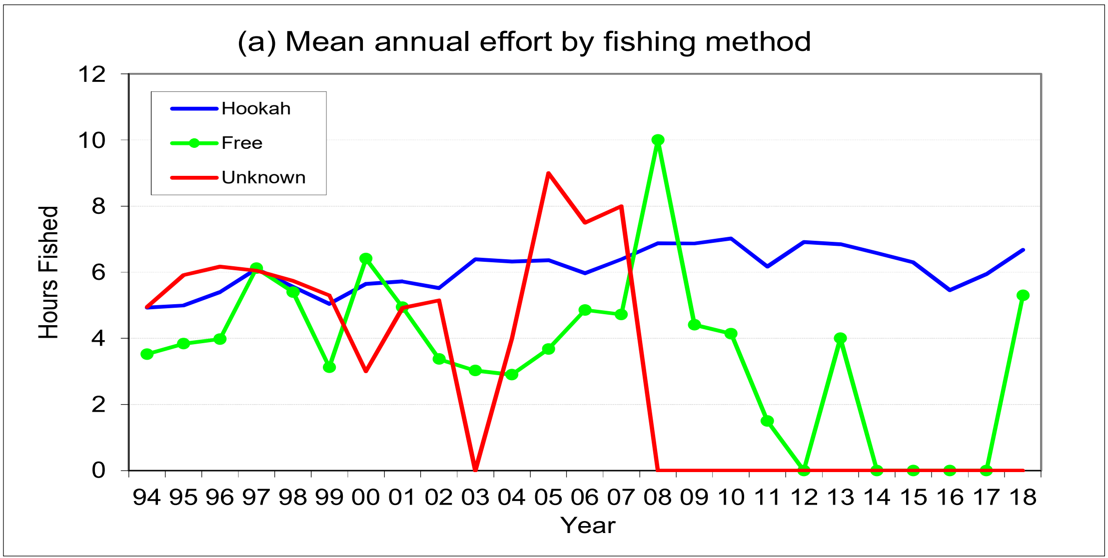
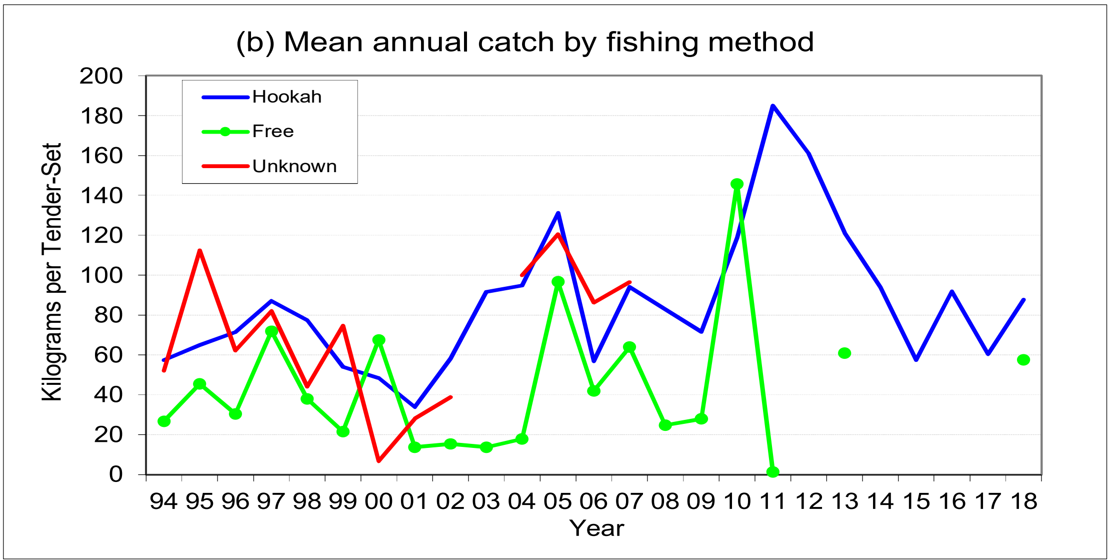
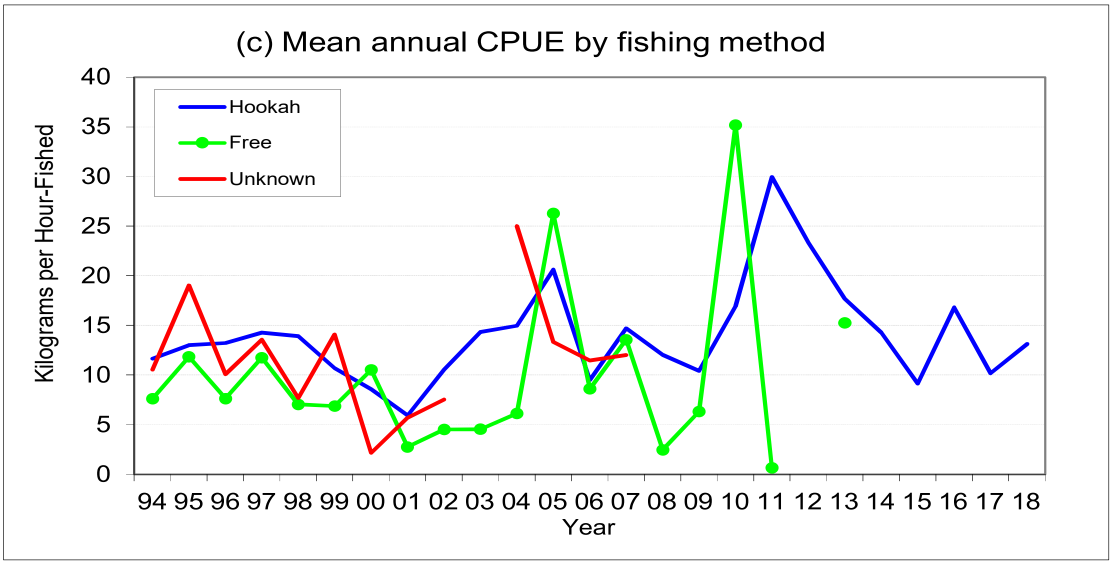



Figure 5. Mean (a) effort, (b) catch and (c) CPUE by fishing method and year for the 51,643 unique vessel-day, shot, tender and diving method records for which this effort was between 0 and 12 hours and areas and months restricted as described in the text.



each tender-set is equivalent to a day's effort. However, unfortunately this field has not been completed for all tender-sets, with the number of hours fished recorded for only 56,534 (80.4%) of the 70,283 records. (Note, the proportion of records where the effort was not recorded averaged 32% between 1994 and 2005, but has been less than 5% for most years since 2006, but was 13% in 2010 and again increased to 12.5% in 2017, c.f. Figure 2). The distribution of hours fished for these records is shown in Figure 4. The number of recorded hours fished is between 0.15 hours and 96 hours, though was 12 hours or less for 99.4% of all records. All records where the recorded hours-fished was greater than 12 hours were considered suspect and as such only those records where the hours-fished was 12 hours or less were included in the analysis. The five records where effort was less than 0.5 hours were also excluded. Note, the number of hours fished was recorded as 24 hours for 315 records and was assumed to represent a "day's" fishing.

After applying each of the following filters to the data:

- Exclude MSE-areas 0, 401 and -99
- Exclude Month<2 and Month>9
- Exclude Hours-Fished less than 0.5 hour and greater than 12 hours

the number records included in the data for further analysis was reduced to 51,643. The mean (a) effort, (b) catch and (c) CPUE by fishing method and year for these records are shown in Figure 5.

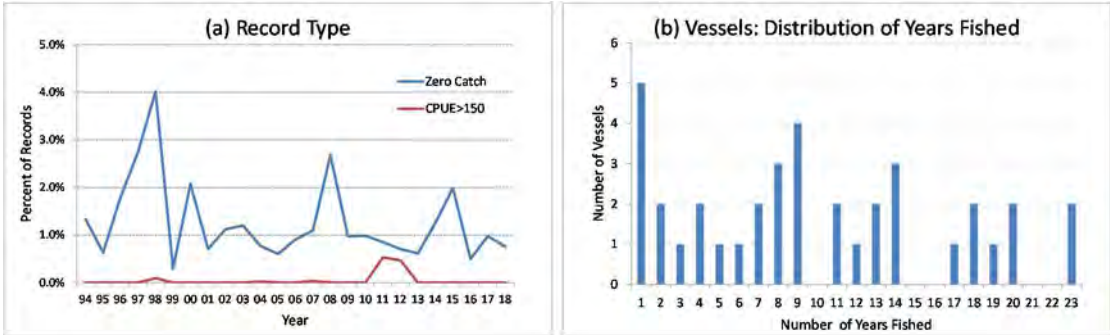
## 2. GLM Analysis

### *i) Fitted Data*

Of the 51,643 records selected above for analysis it was noted that there were a small percentage of records (618 or 1.2%) where the catch was zero. The inclusion of such records in the GLM analyses can cause problems. The percentage of such records each year is shown in Figure 5a and varies from a high of 4.0% in 1998 to a low of 0.29% in 1999. Nevertheless, apart from the four years when this percent was greater than 2% there does not appear to be a trend in the percentage of zero catches in the data over time. As such, and as recommended for the analyses undertaken previously, these zero catch records were excluded from the analyses. Note, to retain the zero-catch records in the analysis a two-stage analysis of the data can be undertaken where one first models the probability of obtaining a positive catch following by a separate analysis where one models the size of the positive catch. The results of each analysis can then be combined to obtain the required standardised CPUE index. Such an approach was not considered appropriate for this data due to the small percentage of zero-catch records in the data.

Further inspection of the data also indicated a number of records having a very high CPUE (kilograms of catch per hour fished) value and which could be considered outliers in the data, possibly due to errors in either the recording of the catch or effort. To exclude these possibilities the 27 records having a CPUE>150 kgs/hour were deleted from the data (cf. Figure 6a). Finally, due to the observation that Vessel-Names and Vessel-Symbols are not always matched (likely due to the switching of licences between vessels) a combination of Vessel-Name and Vessel-Symbol was adopted to identify vessels in the data. Of the 94 vessels identified in this manner in the selected data, only the data pertaining to the 48 vessels which had fished for 3 or more years and for which there were 50 or more data records were included in the analysed data (c.f. Figure 6b. Note only 4 vessels are selected for 2018). Combined with the other two filters the total number of records remaining in the data for analysis was 45,427.

Figure 6. (a) Percentage of records in the data, by year, where either the catch is zero, or the CPUE>150 kg/hour, and (b) histogram of the number of vessels (distinguished by vessel symbol) by the number of years they have fished in the fishery.




The number of *Area-Month* strata fished each year and the number of vessels fishing each year in the data selected for inclusion in the GLM analyses is shown in Figure 7 while a bubble plot displaying the number of observations for each vessel each year in this data is shown in Figure 8. A summary of the number of observations and nominal CPUE (kilograms per hour) within each *Year*Area*, *Year*Month* and *Area*Month* strata is provided in the Appendix.

Figure 7. (a) Number of *Area-Month* strata fished each year and (b) the number of vessels fishing each year in the data selected for inclusion in the GLM analyses.

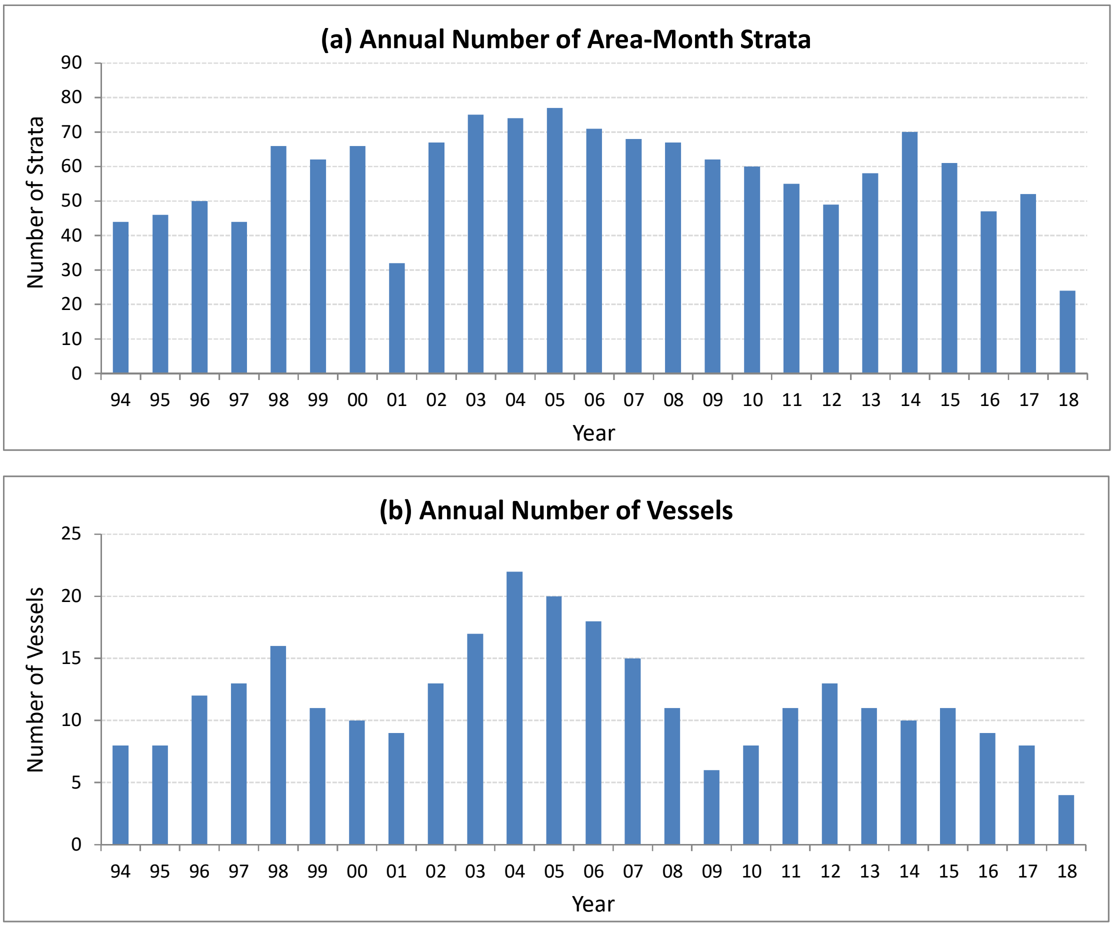
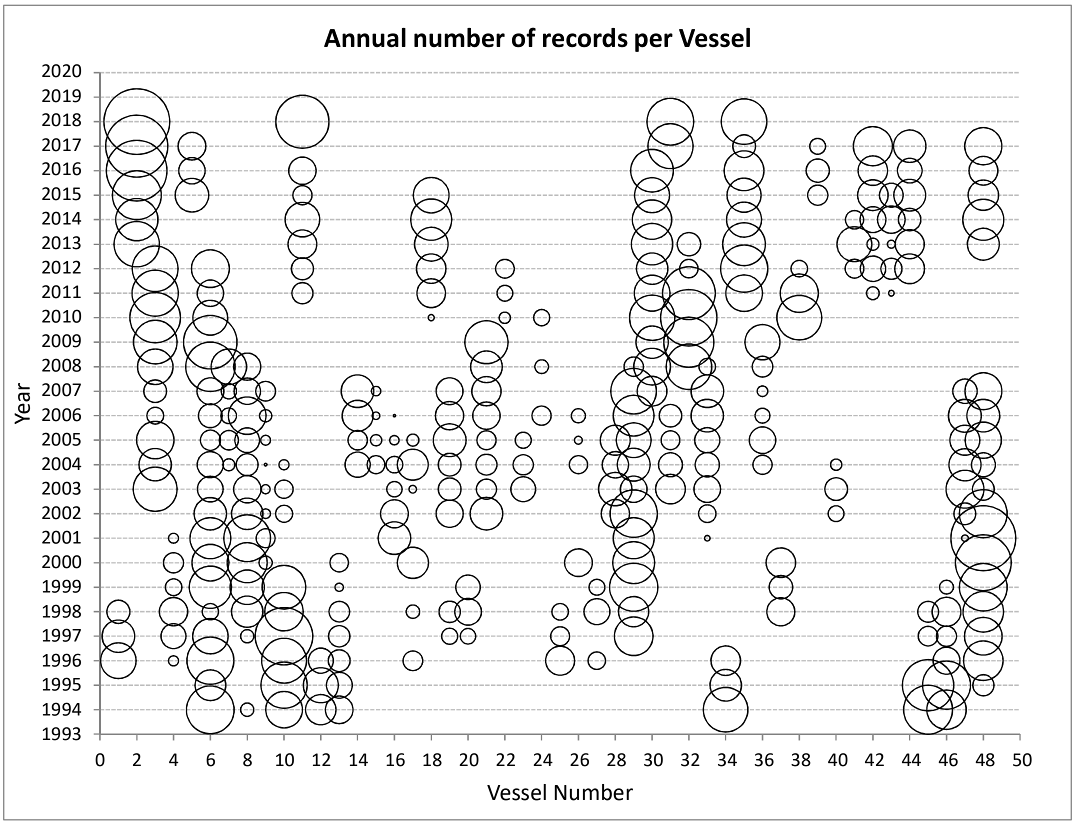


Figure 8. Bubble plot displaying the number of observations for each vessel each year in the data selected for inclusion in the GLM analyses.




*ii) GLM Models*

Several different General Linear Models (GLMs) were adopted for analysing the data in order to obtain a standardised index of stock abundance in each year.

<u>Main Effects Model</u>

In order to explore the impact of each fitted effect, the first set of analyses were based on the following model where no interactions between main effects were included:

*CPUE = Intercept + Year + Month +Area + Vessel +Fishing-Method*
*+ Proportion of Catch Landed as Tails*
*+ Southern Oscillation Index + Moon-Phase*
/ distribution = gamma, link = log

= *I + Y + M + A + V + F + P + SOI + Moon* / dist= gamma, link=log

The SAS GENMOD procedure was used to fit the model. All effects *Year, Month, Area*, *Vessel* and *Method* (Hookah, Free and Unknown) were fitted as class variables except for the SOI index which was fitted as a continuous variable. The *Proportion-Tails* was also fitted as a class variable with each record classified as one of the following five levels: (<20%, 20% to <40%, 40% to <60%, 60% to <80%, >=80%). The monthly values of the *Southern Oscillation Index (SOI)* were used and *Moon-Phase* was modelled as the number of days (0-29) since the last full moon. A log-gamma distribution was assumed for the distribution of CPUE values. The annual index and abundance was determined using the method described in the section below.

For each of the main effects, a measure of the impact of each level on the modelled CPUE was obtained by taking the exponent of the estimated parameter for each level. The impact of each level was then compared to the impact of a reference level. For each main effect these reference levels were:

| | |
|---|---|
| *Month* | September |
| *Area* | Eastern Torres Strait |
| *Method* | Hookah diving |
| *Vessel* | Vessel with the largest number of records |
| *Proportion-tails* | >80% |

Finally, the annual influence of each of the main effects on the resulting index of abundance was calculated using the method described in Bentley et al (2012).

As shown in Campbell (2004) a bias in the annual abundance index can result when there is an unequal number of observations within each spatial-temporal strata used for calculating the abundance index. In order to overcome this problem a weighting of the observations needs to be incorporated when fitting the data to the GLM. Each observation was therefore weighted such that the sum of the weights for all observations in each of the *Year-Month-Area* strata was the same for all strata. Furthermore, in order to account for the weighting given each observation in determination of the annual influence of each main effect the sum of the weights for all observation within a given level was used instead of just the number of observations.

<u>Interactions Models</u>

The second set of analyses was undertaken in order to explore whether the inclusion of 2-way interactions between the main spatial-temporal effects improved the model fit to the data. Specifically, the following five models were examined:

<u>Int-1:</u>

*CPUE = Intercept + Year +Month + Month*Area*
*+ Vessel +Fishing-Method + Proportion-Tails + SOI + Moon*
/ distribution = gamma, link = log

<u>Int-2A:</u>

*CPUE = Intercept + Year*Month + Month*Area*
*+ Vessel +Fishing-Method + Proportion-Tails + SOI + Moon*
/ distribution = gamma, link = log

<u>Int-2B:</u>

*CPUE = Intercept + Year*Area + Month*Area*
*+ Vessel +Fishing-Method + Proportion-Tails + SOI + Moon*
/ distribution = gamma, link = log

<u>Int-2C:</u>

*CPUE = Intercept + Year*Month +Year*Area*
*+ Vessel +Fishing-Method + Proportion-Tails + SOI + Moon*
/ distribution = gamma, link = log

<u>Int-3:</u>

*CPUE = Intercept + Year*Month +Year*Area + Month*Area*
*+ Vessel +Fishing-Method + Proportion-Tails + SOI + Moon*
/ distribution = gamma, link = log

where * indicates an interaction between the related effects. The inclusion in these 2-way interactions allows for the relative distribution of the resource between the different areas and months to be different between years.

*ii) Derivation of Annual Index*

Using the results from each GLM an annual abundance index was constructed based on the standardised CPUE.

For the model which included the three 2-way interactions the standardised CPUE within each Year-Month-Area strata was calculated as follows:

$$stdCPUE(year = y, month = m, area = a) =$$
$$\exp(I + Y.M_{ym} + Y.A_{ya} + M.A_{ma} + F_h + V_{ref} + P_{ref})$$

where $Y.M_{ym}$, $Y.A_{ya}$, $M.A_{ma}$, $F_h$, $V_{ref}$ and $P_{ref}$ are the parameters estimates relating to each of the terms included in the model. Note, due to the over-parameterization inherent in the GLM both $F_h$=0, $V_{ref}$=0 and $P_{ref}$=0 as these respectfully to relate the last levels in each of the *Fishing-Method*, *Vessel* and *Proportion-Tails* factors included in the model. In total there are 1840 (=23 years x 8 months x 10 areas) *Year-Month-Area* strata. As the standardised-CPUE is taken as an index of the density of fish within each strata, an index of the abundance of lobsters across the fishery in each year and month is given by:

$$Index(year = y, month = m) = \frac{1}{\sum_{a=1}^{NA} Area_a} \sum_{a=1}^{NA} Area_a.stdCPUE(y, m, a)$$

where $Area_a$ is the spatial size of each of the *NA Area* effects included in the GLM. Finally, an index of abundance for each year can be obtained by taking the average of the *NM* monthly indices in each year.

$$Index(year = y) = \frac{1}{NM} \sum_{m=1}^{NM} \left[ \frac{1}{\sum_{a=1}^{NA} Area_a} \sum_{a=1}^{NA} Area_a.stdCPUE(y, m, a) \right]$$

Finally, a relative annual abundance index, $B_y$, was calculated such that the mean index over all years equals 1, i..e:

$$B_y = \frac{Index(year = y)}{\frac{1}{NY} \sum_{i=1}^{NY} Index(year = i)}$$

The total spatial size of the each MSE area shown in Figure 9 is unlikely to represent suitable habitat for rock lobsters. As such, in order to ascertain the spatial size of each MSE area to be used in the GLM-analysis, the number of 0.1x0.1-degree squares fished (based on the location of the mother ship recorded in the TVH logbook) within each MSE area was determined for each year. For those squares which included more than one MSE area, the square was apportioned between the different MSE areas based on the proportion of records in each area. Across the entire Torres-Strait region the number of squares fished each year between 1994 and 2018 has varied between 29 (in 2018) and 94 (in 2004) with a mean of 49.3 (c.f. Figure 10). The size of each MSE area $Area_a$, was set to the mean number of squares fished across all years, and then expressed as a percentage of the combined total across all areas so that $\sum Area_a = 1$.

Figure 9. Map of the MSE regions used as the area effects in the GLM.

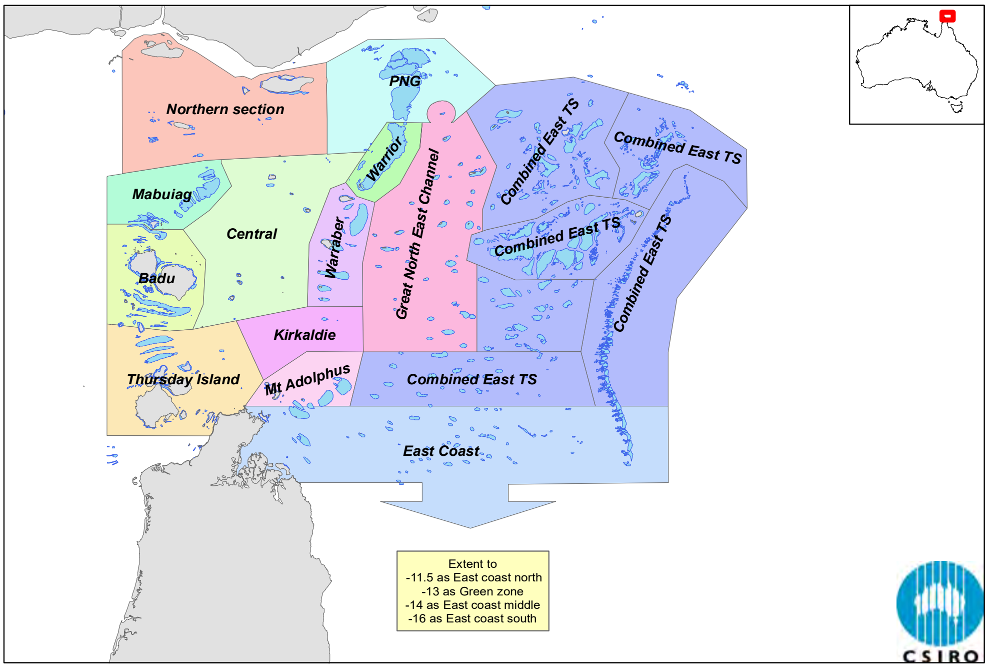
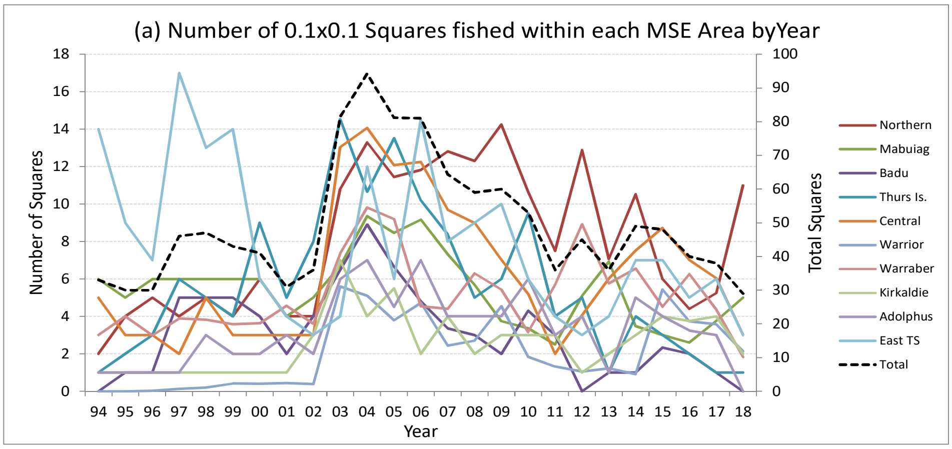
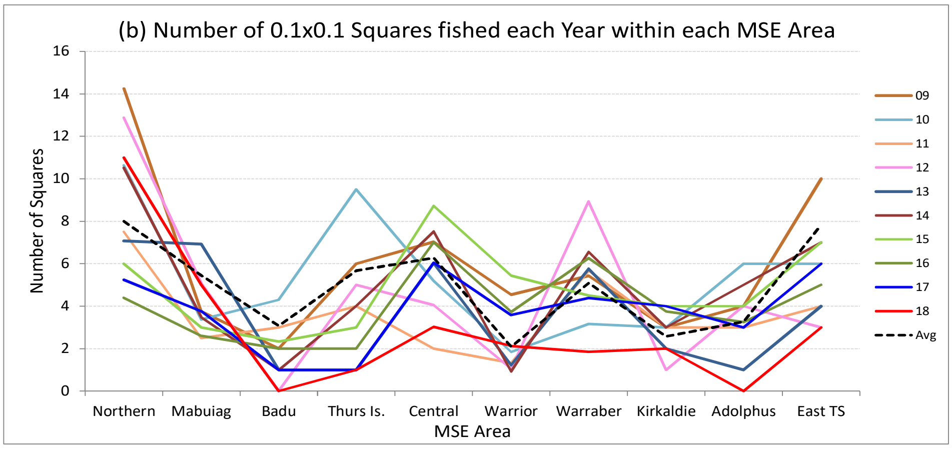



Figure 10. Number of 0.1x0.1-degree squares fished (a) within each MSW area by year, and (b) each year within each MSW area between 2009 and 2018. The average over all years (1994-2018) is also shown in both figures.



The derivation of the abundance index based on the GLMs which included less than three 2-way interaction terms is similar to that shown above. However, it can be noted that for those models which do not included an interaction with the Year effect (i.e. the main effects and Int-1 models), the relative abundance index, $B_y$, reduces to the simpler form:

$$B_y = \frac{\exp(Y_Y)}{\frac{1}{NY}\sum_{i=1}^{NY}\exp(Y_i)}$$

where $Y_i$ , $i=1, NY$ are the parameters estimates relating to the *NY Year* effects included in the model. In these situations the abundance is independent of the relative size of each *Area* effect included in the GLM.

## 3. Results

### *(a) Standardising Effects*

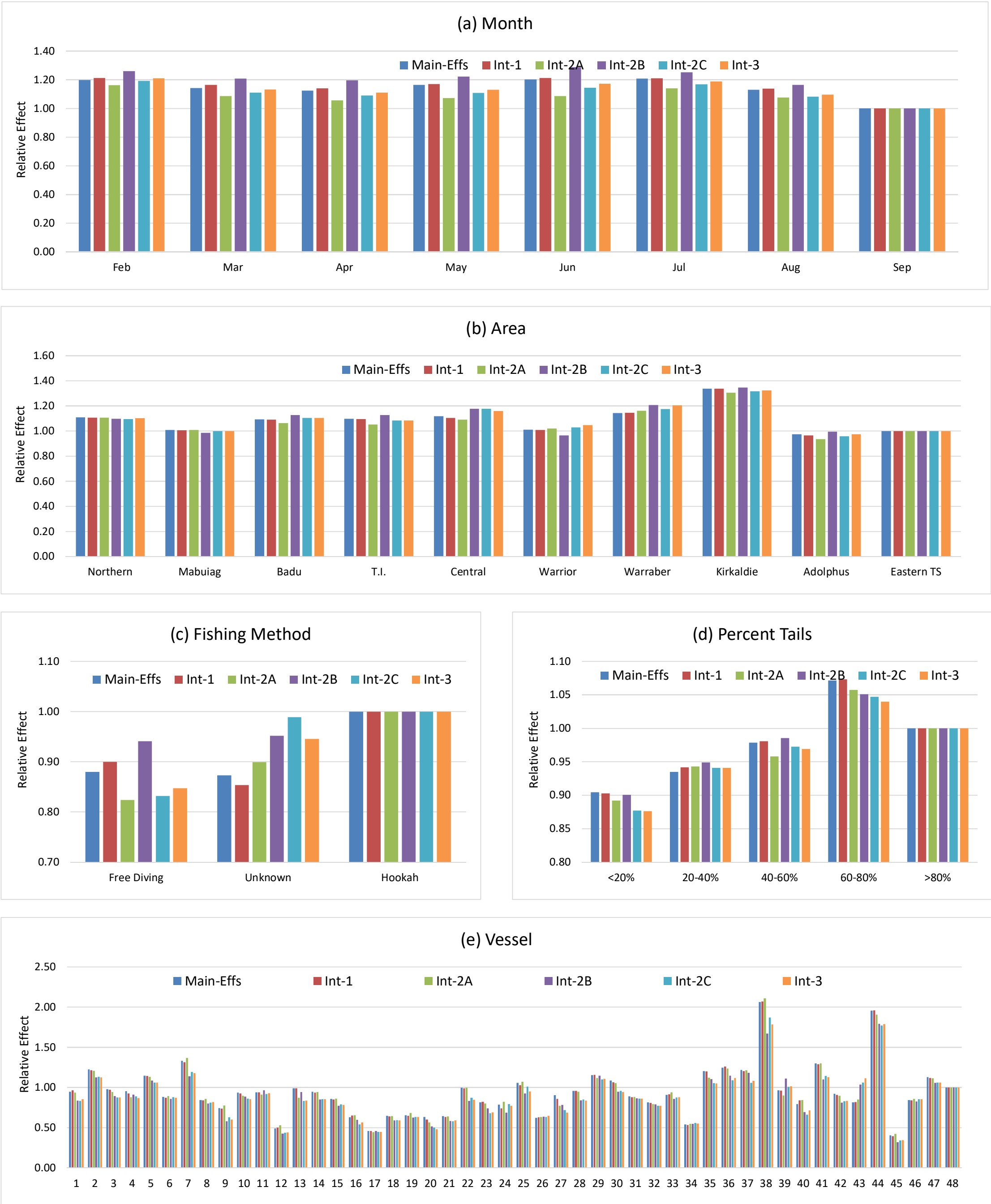
Statistics for the Type 3 contrasts computed for each fitted effect indicated that each effect was highly significant. The relative impact of each level for all effects fitted to each GLM model is shown in Figure 11. For each effect the values have been scaled so that the influence of each level is relative to that of the last level (i.e, *Month*=Sep, *Area*=Eastern TS, *Method*= Hookah and *Proportion-Tail*s >80%). For those models which included interactions the *Quarter* and *Area* effects were determined by calculating the mean effect across all *Year*, *Month* and *Area* strata respectively.

Relative CPUE is relatively constant across the eight months of the year and displays only small variation across the six GLM models, though the CPUE in September is the lowest across all models (c.f. Figure 11a). Taking the average of the relative effect across the results for the six models for each month indicates that the CPUE is highest during February, June and July (18-21% higher than the CPUE in September) while during March, April and May the CPUE is 12-14% higher than the CPUE in September. The greatest variation (as measured by the standard deviation, σ) between models in the relative CPUE across all months is between the results for the 2Ints-A (σ=0.05) and 2Ints-B models (σ =0.09). For all other models σ=0.07.

The relative CPUE across the various areas included in the GLM also do not display large variation across the six GLM models, though there is some degree of variation across the ten areas (c.f. Figure 11b). Taking the mean of the relative effect across the results for the six models for each area indicates that the relative CPUE is, on average, lowest in Mt Adolphus (97%), Eastern TS (100%, the reference area) and Warrior (101%) and highest in Kirkaldie (133%), Warraber (117%) and Central (114%).

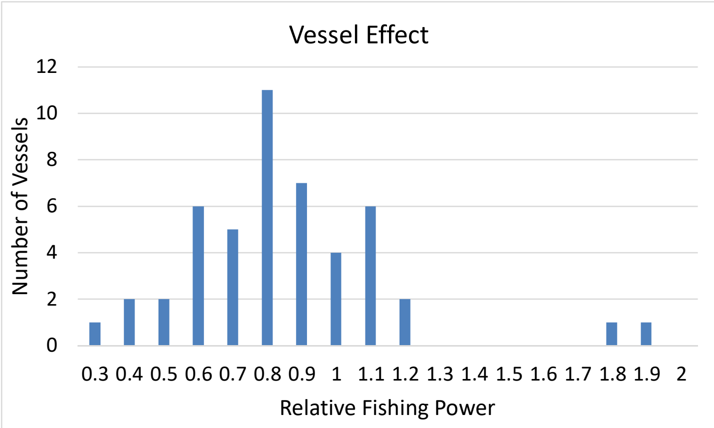
Unlike the previous results, the relative CPUE across the three fishing methods displays larger variation across the six GLM models (c.f. Figure 11c). For example, the relative effect of the free-diving method relative to hookah diving varies between 82% and 94% while that for the unknown method varies between 85% and 99%. Across all models, the CPUE for hookah fishing is found to be around 13% higher than for free diving and 8% higher than for unknown method. This latter result is to be expected if this fishing method is likely to be a combination of the two other fishing methods

Figure 11. Relative impact of each level of the main effects fitted to the each GLM.



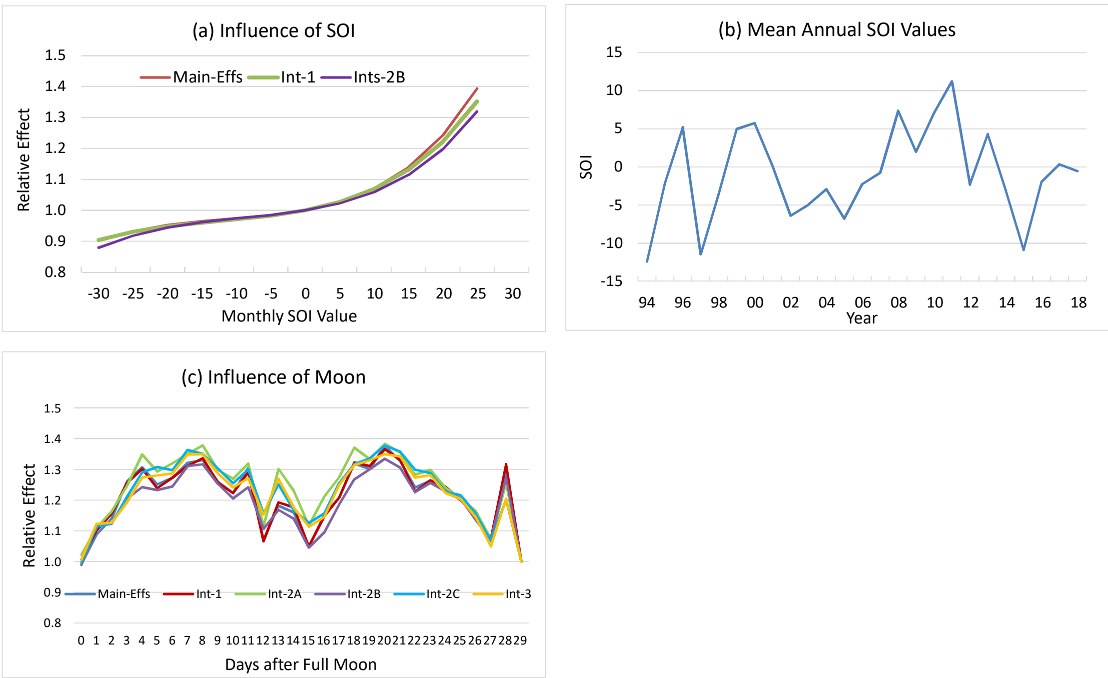

The relative CPUE across all models is similar for each category of the proportion of the catch which is tails with the relative CPUE generally increasing as the *Proportion-Tails* increases in the catch (c.f. Figure 11d). However, the highest CPUE is found for those catches which include 60-80% tails. Across all models, the relative CPUE within each *Proportion-Tails* category is 89%, 94%, 97%, 106% and 100% respectively. Finally, there is substantial variation in the relative CPUE across the 48 vessels included in the GLM models, though the relative effect of each vessel is less sensitive to the GLM model used (c.f. Figure 11e). Across all models, the relative fishing power across the fleet varies more than four-fold from 37% to 193% of the standard vessel and the distribution of these effects is shown in Figure 12.

Figure 12. Histogram of the distribution of the relative fishing power of the 48 vessels included in the GLM models.




The monthly value of the SOI was fitted as a cubic function and the estimated influence of this effect on CPUE based on the results from three of the fitted GLM models is shown in Figure 13a. Note, the influence of SOI on CPUE cannot be estimated for several models as the related parameter is aliased when the GLM model includes a *Year.Month* interaction term. The influence of the SOI is seen to be similar for the three models shown, with negative values of the SOI (El Nino conditions) decreasing CPUE while positive values of the SOI (La Nina conditions) increasing CPUE. This indicates that oceanographic conditions may have influenced the high CPUEs experienced in the fishery in 2011 (when the mean SOI value was 12.7, c.f. Figure 13b) and the low CPUE experienced in the fishery in 2015 (when the mean SOI value was -10.8). However, based on the results shown in Figure 13 the influence on CPUE of the conditions prevailing in these years should have been only 6-7%. Further exploration of the influence of this and other environmental variables is warranted.

Figure 13 (a) Relative influence of the values of the SOI on CPUE and (b) mean annual values of the SOI since 1994. (Note, SOI value for 2017 only mean from Jan to Nov).



Finally, the influence of the daily moon-phase across each of the GLM models is shown in Figure 13c. The influence is seen to be similar across all models and displays an interesting bi-modal distribution across the days between successive full moons. CPUE is lowest during days near a full moon and also low around a new moon, while CPUE is highest mid-way between these two phases (i.e. around the first and last quarters). During this latter periods CPUE is around 30% higher than at the time of a full moon.

*(b) Annual Abundance Indices*

The relative abundance indices based on each of the six GLM models are listed and displayed in Table 4 and Figure 14 respectively. Relative to the nominal index, each of the standardised indices is similar but is higher at the start of the time-series and lower after 2012. The reasons for these differences can be investigated using the annual influence of each main effect which is shown in Figure 15 for the Main-Effects and Int-1 models. The influence on the annual index is seen to be greatest for the *Vessel* effect followed by the *Proportion-Tails* effect, with the influence of each effect showing an opposing trend over time. The change in the influence of the *Proportion-Tails* effect correlates with the shift from the catch being all tails to now being predominantly whole (c.f. Figure 3b), which decreases CPUE (c.f. Figure 11d), while the change in the influence of the *Vessel* effect is most likely due to an (expected) increase in the relative fishing power of vessels over time. The relative influence of the *Vessel* effect is seen to be greatest towards the start and end of the time- series and explains the divergence seen between the nominal and standardised indices at these times.

Table 4. Annual abundance indices for Torres Strait rock lobsters based on the standardised CPUE from the weighted GLM models. The nominal CPUE is also shown for comparison.

| Year | Nominal | Main-Effs | Int-1 | Int-2A | Int-2B | Int-2C | Int-3 |
|---|---|---|---|---|---|---|---|
| 94 | 0.89 | 1.40 | 1.41 | 1.32 | 1.38 | 1.35 | 1.35 |
| 95 | 0.97 | 1.39 | 1.38 | 1.30 | 1.35 | 1.32 | 1.33 |
| 96 | 0.94 | 1.01 | 1.01 | 1.01 | 1.03 | 1.00 | 1.01 |
| 97 | 1.04 | 1.17 | 1.16 | 1.11 | 1.11 | 1.08 | 1.08 |
| 98 | 0.98 | 1.07 | 1.07 | 1.07 | 1.09 | 1.10 | 1.09 |
| 99 | 0.77 | 0.67 | 0.67 | 0.68 | 0.66 | 0.67 | 0.67 |
| 00 | 0.62 | 0.68 | 0.67 | 0.74 | 0.65 | 0.72 | 0.73 |
| 01 | 0.44 | 0.44 | 0.44 | 0.43 | 0.47 | 0.47 | 0.47 |
| 02 | 0.77 | 0.69 | 0.69 | 0.66 | 0.67 | 0.63 | 0.63 |
| 03 | 1.03 | 1.08 | 1.07 | 1.03 | 1.05 | 1.02 | 1.01 |
| 04 | 1.09 | 1.17 | 1.17 | 1.16 | 1.16 | 1.12 | 1.14 |
| 05 | 1.49 | 1.49 | 1.49 | 1.42 | 1.47 | 1.38 | 1.40 |
| 06 | 0.68 | 0.69 | 0.70 | 0.68 | 0.67 | 0.65 | 0.65 |
| 07 | 1.08 | 1.00 | 1.00 | 0.97 | 1.00 | 0.96 | 0.96 |
| 08 | 0.87 | 0.84 | 0.84 | 0.87 | 0.89 | 0.91 | 0.90 |
| 09 | 0.62 | 0.65 | 0.65 | 0.64 | 0.69 | 0.69 | 0.69 |
| 10 | 1.24 | 1.09 | 1.10 | 1.24 | 1.14 | 1.24 | 1.27 |
| 11 | 2.11 | 1.75 | 1.75 | 1.93 | 1.94 | 2.13 | 2.09 |
| 12 | 1.64 | 1.46 | 1.46 | 1.43 | 1.36 | 1.33 | 1.30 |
| 13 | 1.27 | 1.23 | 1.23 | 1.28 | 1.24 | 1.29 | 1.30 |
| 14 | 1.04 | 0.94 | 0.94 | 0.93 | 0.94 | 0.92 | 0.92 |
| 15 | 0.63 | 0.58 | 0.58 | 0.56 | 0.54 | 0.52 | 0.52 |
| 16 | 1.19 | 1.04 | 1.05 | 1.09 | 1.05 | 1.05 | 1.08 |
| 17 | 0.75 | 0.68 | 0.68 | 0.66 | 0.70 | 0.66 | 0.64 |
| 18 | 0.88 | 0.79 | 0.78 | 0.79 | 0.77 | 0.79 | 0.78 |
| Mean | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

Figure 14. Annual abundance indices for Torres Strait rock lobsters based on the standardised CPUE from the Main-Effects and several interaction models. The nominal CPUE is also shown for comparison.

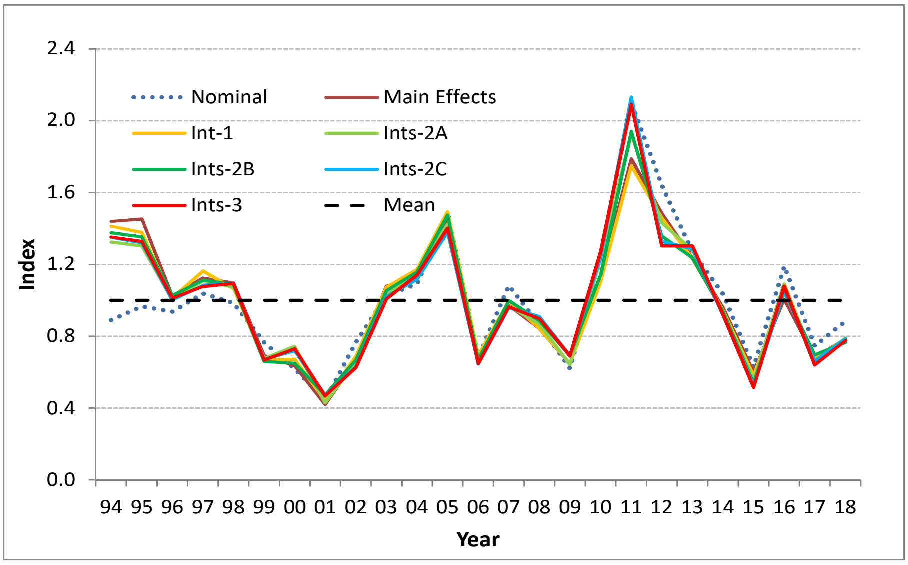



Figure 15. Annual influence of the fixed effects fitted to (a) the Main-Effects model and (b) the Int-1 model.

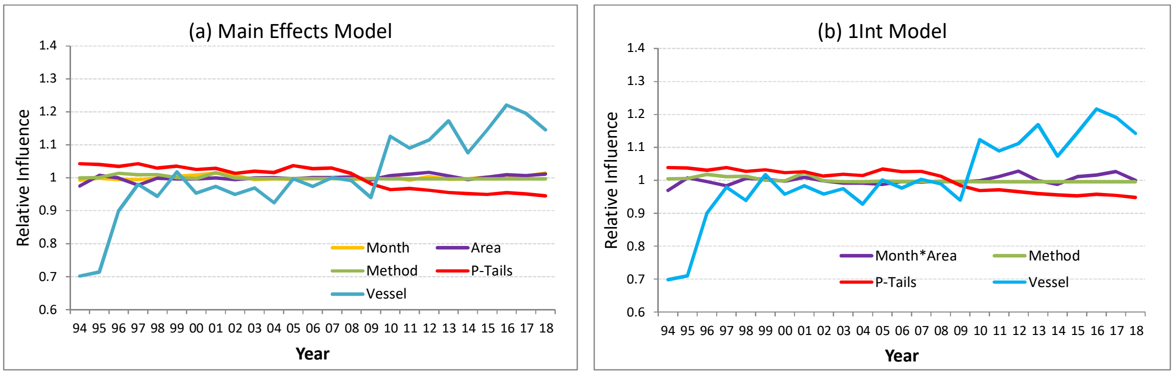



Table 5. Criteria for assessing the goodness-of-fit of each GLM.

| GLM | Main | Int-1 | Int-2A | Int-2B | Int-2C | Int-3 |
|---|---|---|---|---|---|---|
| N-records | 45,427 | 45,427 | 45,427 | 45,427 | 45,427 | 45,427 |
| df | 128 | 188 | 350 | 393 | 490 | 553 |
| Deviance | 20,133 | 19,810 | 18,467 | 17,923 | 17,084 | 16,739 |
| Chi-sq | 21,313 | 20,794 | 18,845 | 18,038 | 17,014 | 16,580 |
| likelihood | -172,861 | -172,443 | -170,638 | -169,874 | -168,651 | -168,132 |
| AIC | 345,975 | 345,266 | 341,977 | 340,534 | 338,282 | 337,370 |
| BIC | 347,083 | 346,923 | 345,030 | 343,963 | 342,556 | 342,194 |
| N-Strata | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 |
| Imputed | 0 | 0 | 50 | 88 | 126 | 126 |

The influence of the other effects is seen to be relatively small. For the *Area* and *Month* effects this is likely to be due to the equal weighting given to each *Year-Month-Area* strata in the GLM model analysis. The small but positive trend in the influence of the *Method* effect over the time-series also relates to the fact that there may have been a slight increase in the proportion of catches using hookah diving over time (c.f. Figure 3a) which has the highest CPUE (c.f. Figure 11d).

Several criteria for assessing the goodness-of-fit for each of the GLM models are shown in Table 5. For each criteria shown (where smaller is better) there is an improvement in the fit between each successive model implying that the model which includes all three 2-way interactions provides the best fit to the data. The Int-3 model has considerably greatly flexibility in accounting for inter-annual changes in the distribution of the resource across the different months and areas in comparison to the Main-Effects model which assumes that these distributions are the same for all years. However, the number of parameters (553) estimated in the full interaction model Int-3 is considerably greater than the number of parameters (128) estimated in the Main-Effects model. A consequence of the increase in the number of parameters is that the number of observations on which some of the parameters rely to be estimated can be small (or in some instances zero). A small number of observations increases the likelihood that the corresponding parameter is poorly estimated.

Figures showing of the number of observations per 2-way strata (for which a separate parameter was estimated) are shown in the Appendix. For 36 (14.4%) of the 250 *Year*Area* strata the number of observations was less than 10 (with 13 of these strata having zero observations) while only six of the 200 *Year*Month* strata had less than 10 observations (being zero for five strata, four of which occurred in 2018). On the other hand, the number of observations was greater than 13 for all of the 80 *Area*Month* strata. For those strata for which the number of observations is zero, the related standardised CPUE for these strata needs to be imputed. (Note, the number of strata for which the standardised CPUE needs to be imputed for each model is shown in Table 5.) For this purpose, the corresponding value using the Int-1 model was used as this model allows the standardised CPUE to be calculated within all strata.

For the Int-3 and Int-2C models, the number of *Year-Month-Area* strata where no observations were available for estimating the related model parameters (which then needed to be imputed) was 126 (or 6.3% of the 2000 number of strata in total). For the Int-2B model the number of imputed strata was 88 (4.4%) while the number of imputed strata for the Int-2A model was 50 (or 2.5% of all strata). While it is can be considered best practice to select an abundance index where no parameters have had to be estimated (i.e. the Main-Effects or Int-1 models), the small number of estimated parameters in the Int-2A model reduces the potential for bias in the corresponding index.

## 4. Concluding Remarks

The above analyses, and the resulting indices of annual abundance, are based on the number of assumptions about the data and how these data describe fishing behaviour in the fishery. In particular, if there are features of the fishery which are not adequately captured by the data used in these analyses then the GLMs will not be able to standardise the CPUE for these particular features.

For example, even though the inclusion of interactions allows the model the freedom to the resolve differences in the distribution of the resource across the different areas within different years, the model has no ability to resolve changes in the fishery which may take place within any given area (or month). In particular, the models used to standardise CPUE assume that within each year the distribution of fishing effort within any area is relatively random or that the pattern of fishing across each area remains relatively consistent over time. However, it is possible that with the introduction of new technologies (such as GPS) that over time fishers have been able to more precisely target their fishing effort to sub-regions of preferred habitat (and higher abundance) within a given area. Such 'effort creep' would result in higher catches and higher CPUE compared to the situation where no new technologies were available. The maintenance of high CPUE in light of reduced resource abundance due to effort creep (known as hyper-stability) ultimately leads to a breakdown of the linear relationship assumed between CPUE and resource abundance.

This can be a particularly critical consideration for an aggregating species such as rock lobsters, when higher CPUE can be maintained when fishers can target known aggregating sites, or the number, size and the distribution of such aggregations within a season can change in response to changes in ambient conditions within a season not related to overall abundance (e.g. oceanographic conditions). It is interesting to note that the area fished across the fishery (as measured by the number of 0.lx0.1-degree squares, c.f. Figure 10a) has been decreasing over time, with the area fished reaching a minimum during the current year (2018). However, whether this indicates that the fishing effort was more aggregated during 2018 than in other years remain uncertain, as the location of fishing effort currently recorded in the logbook is the location of the primary vessel and not the associated tenders which can disperse themselves widely from the primary vessel.

While the fitted GLM models used in the analyses described in this report appear to capture increases in the fishing power of the fleet due to changes in the vessels leaving and entering the fishery, continual increases in the fishing power over time for individual vessels that remain in the fishery will not be captured by the available data and fitted models and as such could result in continual biases in the calculated indices of abundance.

To help overcome this problem it would be useful to further investigate whether or not there have been increases in fishing power over time which are not currently captured by the data. With such information in hand one could then decide whether the data currently available adequately captures the strategies used in the fishery. If not, there needs to be a further discussion as to what additional data may need to be collected so that these aspects of the fishery can be taken into account in the statistical analyses used to standardise the data. Of course, this is a discussion that is pertinent to all fisheries.

Finally, the catches and catch-rates achieved in a fishery are also likely to be influenced by changes in oceanographic and environmental conditions which are likely to change on both a seasonal and inter-annual basis. While the current analyses attempt to model the influence of the monthly value of the Southern Oscillation Index (used to distinguish El Nino and La Nina conditions) and the daily phase of the moon on catch rates, the influence of such environmental changes is likely to require a broader understanding of oceanographic processes that impact on the fishery (including those which may influence the aggregation dynamics of the rock lobsters and delayed effects such as those which influence recruitment success or failure and which subsequently propagate through the fishery over time). Again it would be useful to discuss how such processes can be incorporated into these models.

The use of standardised CPUE as an index of resource abundance is an important input to the stock assessments for many fisheries. This is particularly the situation for those fisheries where fishery independent surveys of the resource are not available or feasible (such in fisheries for highly migratory species such as tunas and billfish). However, as noted above the accuracy of these indices is premised on a number of assumptions, particularly the ability of the logbook data used in the analyses to readily capture the important aspects of the fishery which influence catch rates. In these instances, and where possible, it is useful to incorporate fisheries independent data into the stock assessments. In particular, annual indices of resource status based on fishery independent surveys are usually seen as an important adjunct to the fishery dependent data, and where possible their inclusion in the stock assessment is highly recommended. Where such surveys are not available then attention needs to be paid to ensuring that the logbook data from the fishery captures the information necessary to adequately standardise the catch rates in the fishery as discussed above.

For the Torres Strait rock lobster fishery there are currently two sources of catch and effort data, those for the TVH and TIB sectors. The logbook data from the TVH sector is believed to provide a relatively complete and good source of catch and effort data for this sector, though improvements in compliance to ensure that all fields in the logbook are completed (e.g. area fished and hours fished) would improve the utility of these data. Also, a better recording of the locations of the fishing effort (i.e. at the tender level) would also improve the accuracy of the data for standardising catch rates. On the other hand, the data for the TIB sector is considered to be less complete and the measure of effort (days fished) is less accurate and incomplete in many instances. While the utility of these data to provide a useful index of resource abundance has been investigated elsewhere (Campbell et al, 2017), again greater effort needs to be placed on ensuring the completeness and accuracy of these data for such purposes.

## References

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# Appendix: Data Summary

The following three spatial-temporal effects were included in the GLM used to standardise the CPUE for lobsters caught in the Torres Strait:

1) Year (all 25 years between 1994 and 2018)
2) Month (all 8 months between February and September)
3) MSE-Area (10 areas)

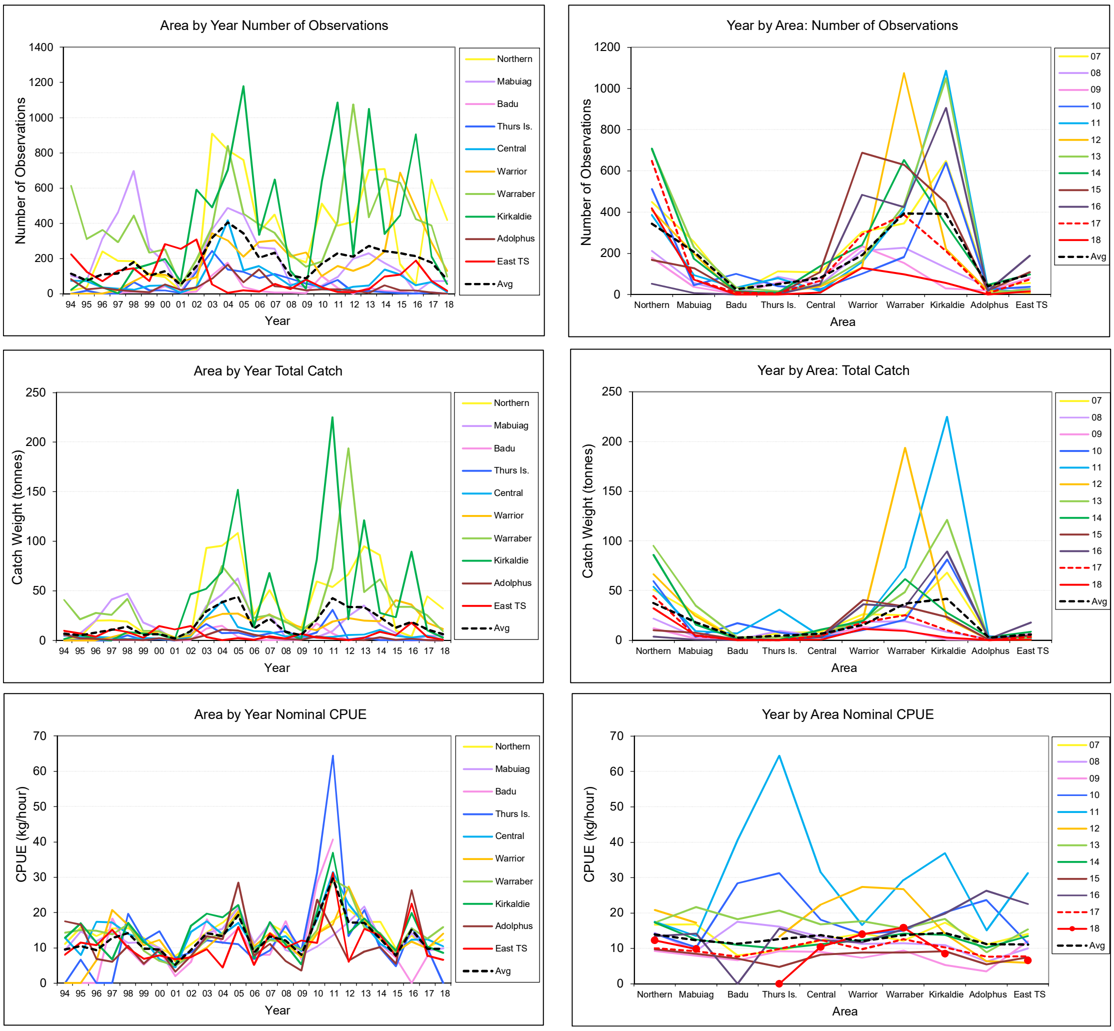
For each 2-way combination of these effects, the following figures provide:

1) Number of data observations
2) Total catch (kilograms of lobsters)
3) Nominal CPUE (kilograms per hour fished)

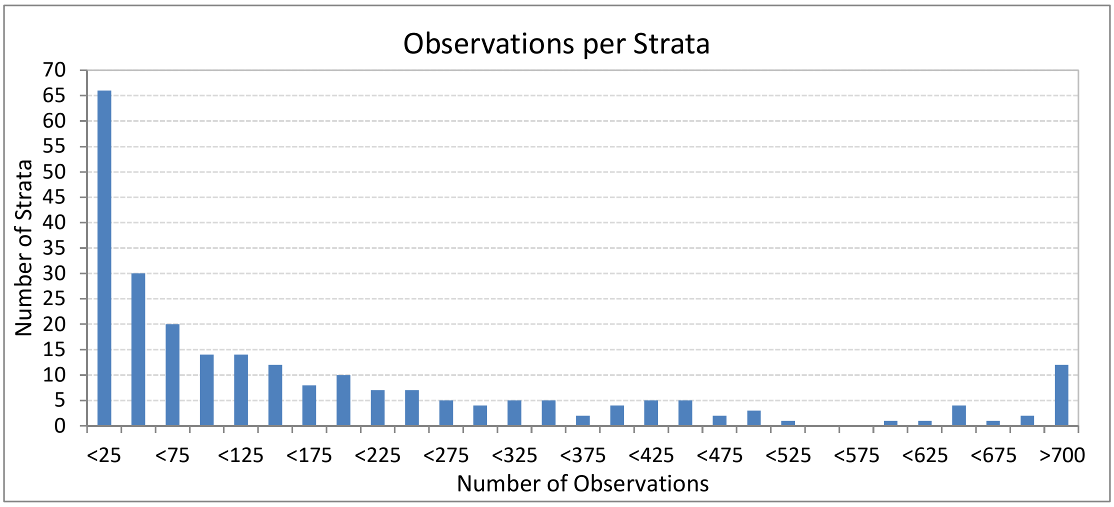
The data is limited to those records fitted to the GLMs and includes 45,427 records.

A histogram of the number of observations within each stratum is also shown for each of the above 2-way combination of these effects.

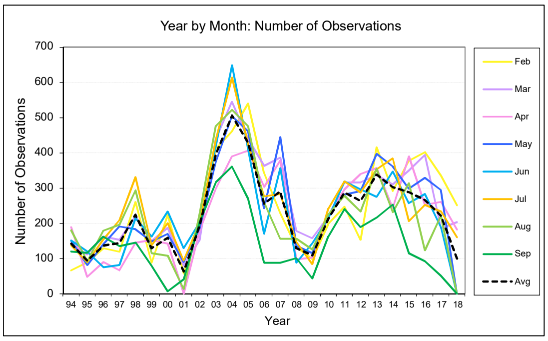
## (a) Year*Area

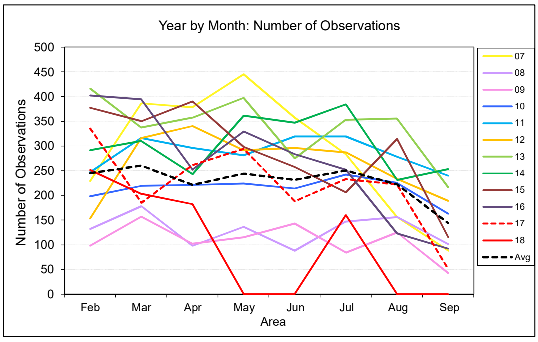


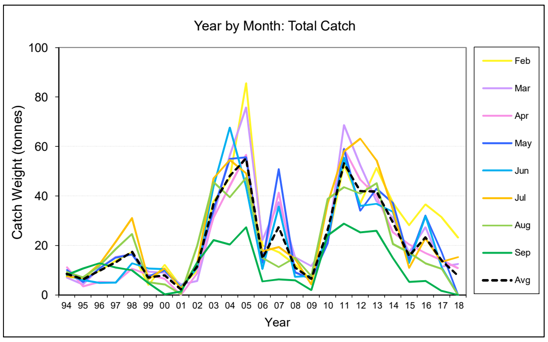

Of the 250 Year*Area strata (25 years x 10 areas) the number of observations is zero for 13 strata: There are a further 8 strata where the number of observations was between 1 and 4 and 15 strata where the number of observations was between 5 and 9. The number of observations for all other strata was between 10 and 1,178.

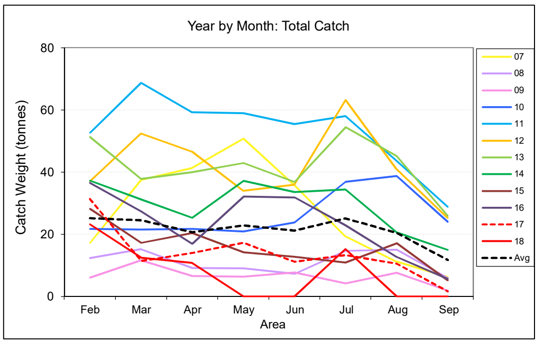


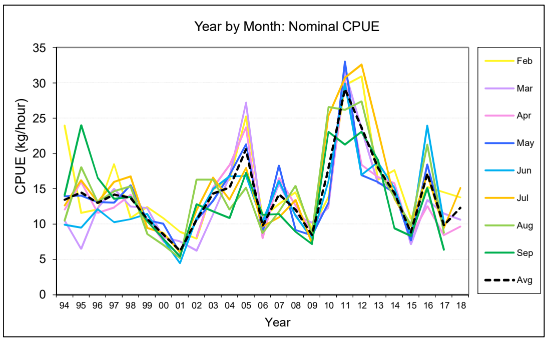
## (b) Year*Month

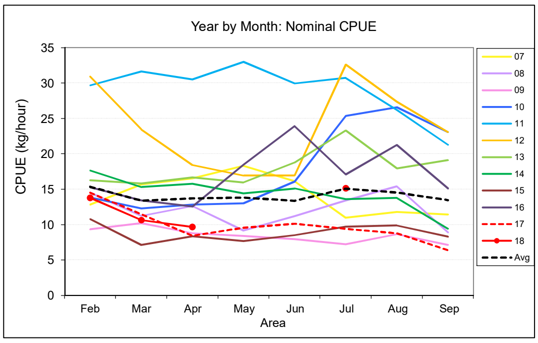


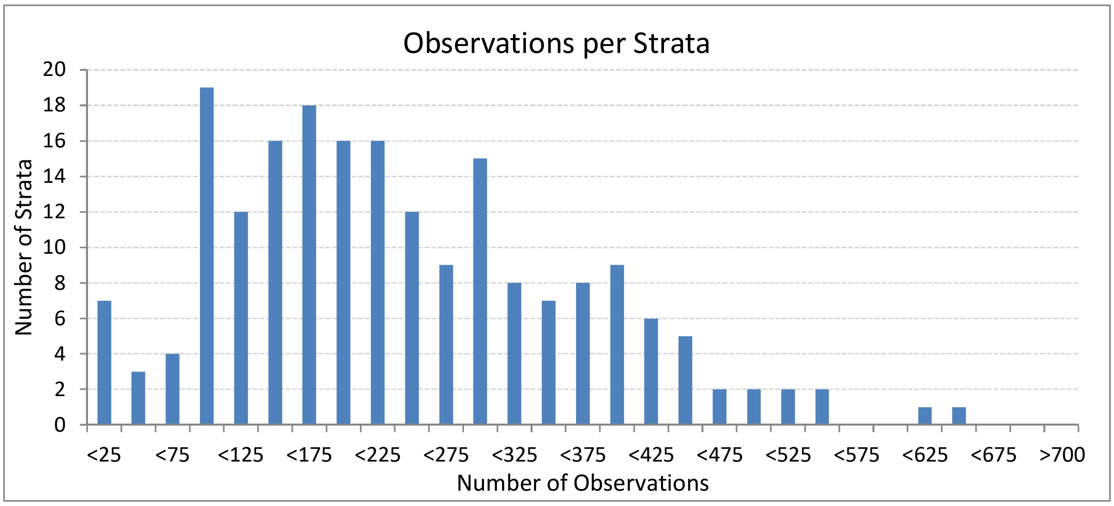



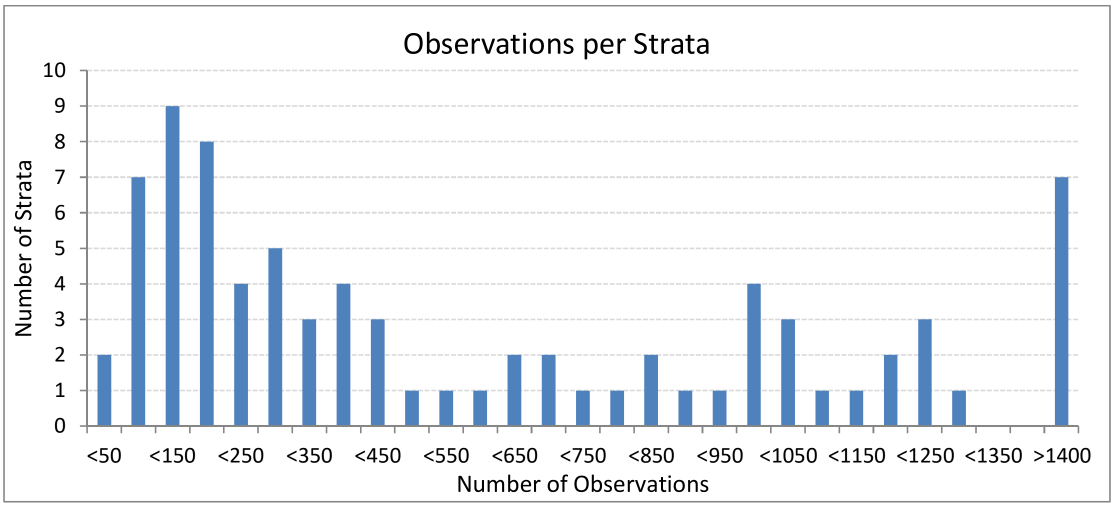




Of the 200 Year*Month strata (25 years x 8 months) the number of observations is zero for 5 strata (Apr-01 and May-Jun-18 & Aug-Sep-18). There was one strata (Sep-00) with only 7 observations. For the remaining 194 strata the number of observations was between 10 and 649.



## (c) Month*Area


Of the 80 Month*Area strata (8 months x 10 areas) the number of observations for all strata was between 37 and 1,685.



# Use of TIB Docket-Book Data to construct an Annual Abundance Index for Torres Strait Rock Lobster – 2018 Update

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CSIRO Oceans and Atmosphere Flagship

October 2018

## 1. Introduction

The Torres Strait Seafood Buyers and Processors Docket Book (TDB01), until recently, was used in the TIB sector of the Torres Strait rock lobster fishery to record the catch sold by fishers (known as sellers on the Docket-Book) at the end of a fishing trip. It was replaced on 1 December 2017 by the mandatory Torres Strait Catch Disposal Record TDB02. However, unlike the Daily Fishing Log (TRL04) used in the TVH sector of fishery, which requires catch and effort data to be recorded for individual fishing operations related to each vessel tender, both the TDB01 and TDB02 Docket-Books require only aggregate catch and effort data to be recorded at the end of each trip. Nevertheless, both sets of catch and effort data recorded in each sector of the fishery have proven useful in constructing abundance indices for the fishery, and both are included in the Harvest Control Rule used to help determine an appropriate annual TAC. This document provides the latest update of the data and analyses undertaken for constructing the abundance index based on the Docket-Book data for the TIB sector (see Campbell *et al*, 2017).

## 2. Estimation of Total TIB Catch

A copy of both the TDB01 and TDB02 Docket-Books are shown in Appendix A. Each docket-book records the transaction date, the name of the seller, together with details of the catch (in weight). Additional information is also provided regarding the vessel, the number of crew, the number of days fished and the fishing methods used. This information therefore provides a measure of both the catch and effort for a given seller (or fisher) during a fishing trip and hence can be used to gain a measure of the catch rate (weight of lobsters caught per day fished) during that trip.

However, there were a number of issues with the TDB01 Docket-Book system which created problems with using this data for estimating the total catch and effort in the TIB fishery. These issues included:

i. The requirement that completion of this docket-book was only voluntary,
ii. The fact that catches recorded in this docket-book could also be reported elsewhere, including the TVH logbook,
iii. The fact that processors could also record catches in this docket-book, essentially creating duplicates.

Given the duplication of catch information from both the TVH sector and processors which occurred in the TDB01 docket-book data, several filters have been developed and applied to the data sourced from this docket-book in an attempt to identify and remove these duplicates. Further to these issues, several large TIB boats prior to 2016 only recorded their catch in the TVH-related logbook (TRL04) and these catch records need to be transferred to the TIB database. This occurred because some TIB operators believed the TRL04 Logbook was mandatory, though they later became aware reporting for TIB is currently voluntary.

Finally, between 2013 and 2016 several processors reported aggregate annual catch data to AFMA as these catches were not being recorded in the TDB01 Docket-Book. Each processor reported the catch for tailed and whole lobsters separately, so that for each season two catch records were added to the TIB database for each processor to account for these additional catches.

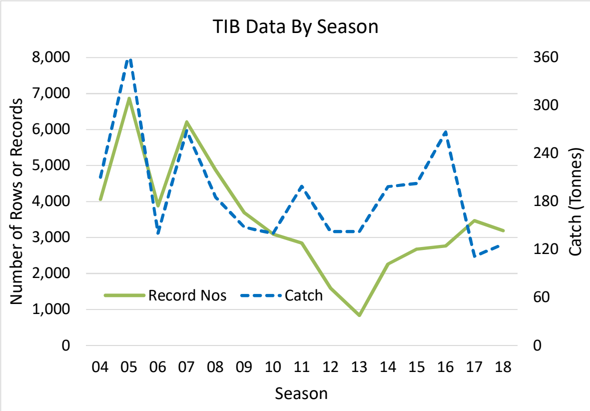
Considerable effort has gone into understanding the nature of both the TDB01 Docket-Book and TRL04 Logbook data so as to identify the catch records that should be assigned to the TIB sector of the fishery. A full description of the approach and data-rules used to identify and remove these duplicate records from the Docket-Book data is described in Campbell and Pease (2017). For the analyses described in this report, a total of 49,130 catch records have now been attributed to the TIB fishery covering the 2004 to 2017 seasons while an additional 3,193 TIB catch records have been sourced from the TBD02 docket-book for the 2018 season. Note, several (54) Docket-Book records having a zero catch of lobsters are not included in these totals as it is assumed that other species may have been targeted on these trips. Also, a catch record for the purpose of the data summarised in this report pertains to the catch and effort information provided on a single page in either the TDB01/TDB02 Docket-Books or TRL04 Logbook and for which a unique Record-Number (Record-No) is attributed. Within the TIB database there are usually multiple rows of catch information associated with each unique Record-No as the catch is separately recorded by process form and perhaps grade.

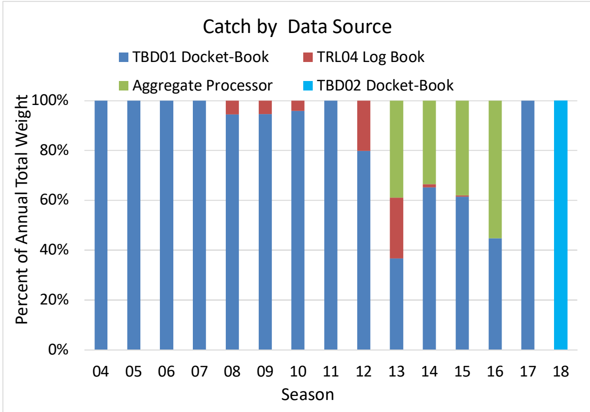
The number of catch records and the associated estimate of the total catch of rock lobsters in the TIB sector each season (starting 1-December), and by data source, is shown in Table 1 and Figure 1. Between 2004 and 2007 all TIB related catch is sourced from the TDB01 Docket-Book, and the number of catch records each season varied between 4,058 and 6,867, while between 2008 and 2015 a portion of the total catch was recorded in the TRL04 Logbook. While the related catch was small in some seasons (<10 tonnes) this catch nevertheless represented over 20% of the total TIB catch in both the 2012 and 2013 seasons. Finally, between 2013 and 2016 a significant portion of the total TIB catch (between 34% in 2014 and 55% in 2016) was attributed to the aggregate catch data provided by several processors (as this catch was not recorded in the TDB01 Docket-Book). For the 2017 season the catch data was sourced entirely

Table 1. Number of distinct TIB Record Nos by fishing season and the related catch by data source. Note, PRC relates to the aggregate catch provided by several processors.

| | Records by Data Source | | | | Total | Catch by Data Source | | | | Total Catch |
|---|---|---|---|---|---|---|---|---|---|---|
| Season | TDB01 | TDB02 | TRL04 | PRC | Records | TDB01 | TDB02 | TRL04 | PRC | (kg) |
| 2004 | 4058 | 0 | 0 | 0 | 4,058 | 210,383 | 0 | 0 | 0 | 210,383 |
| 2005 | 6867 | 0 | 0 | 0 | 6,867 | 367,615 | 0 | 0 | 0 | 367,615 |
| 2006 | 3882 | 0 | 0 | 0 | 3,882 | 140,451 | 0 | 0 | 0 | 140,451 |
| 2007 | 6212 | 0 | 0 | 0 | 6,212 | 268,689 | 0 | 0 | 0 | 268,689 |
| 2008 | 4768 | 0 | 114 | 0 | 4,882 | 175,442 | 0 | 10,223 | 0 | 185,665 |
| 2009 | 3596 | 0 | 95 | 0 | 3,691 | 139,850 | 0 | 7,964 | 0 | 147,814 |
| 2010 | 3033 | 0 | 62 | 0 | 3,095 | 134,353 | 0 | 5,686 | 0 | 140,039 |
| 2011 | 2845 | 0 | 0 | 0 | 2,845 | 199,061 | 0 | 0 | 0 | 199,061 |
| 2012 | 1424 | 0 | 168 | 0 | 1,592 | 113,622 | 0 | 28,757 | 0 | 142,379 |
| 2013 | 649 | 0 | 183 | 2 | 834 | 52,249 | 0 | 34,862 | 55,411 | 142,522 |
| 2014 | 2224 | 0 | 32 | 2 | 2,258 | 129,657 | 0 | 2,456 | 66,662 | 198,775 |
| 2015 | 2652 | 0 | 25 | 2 | 2,679 | 124,369 | 0 | 1,333 | 76,904 | 202,606 |
| 2016 | 2762 | 0 | 0 | 4 | 2,766 | 119,756 | 0 | 0 | 147,380 | 267,136 |
| 2017 | 3469 | 0 | 0 | 0 | 3,469 | 111,504 | 0 | 0 | 0 | 111,504 |
| 2018 | 0 | 3193 | 0 | 0 | 3,193 | 0 | 126,476 | 0 | 0 | 126,476 |
| Total | 48,441 | 3,193 | 679 | 10 | 52,323 | 2,287,001 | 126,476 | 91,281 | 346,357 | 2,851,115 |

Figure 1. (a) Number of distinct TIB catch records and associated catch (in tonnes) by fishing season, and (b) the proportion of the annual TIB catch by data source.




from the TDB01-Book data, being the first time since 2007, and this change was likely the result of requests by AFMA for the Docket-Book to be used for the recording all catches. While it has been noted that a substantive portion of the total TIB catch was reported in aggregate form between 2013 and 2016, and which helps to explain the lower number of Record-Nos during this period, the large reduction in Record-No in 2012 and 2013 appears anomalous. Whether or not other catches were also not been recorded in the Docket-Book during these or in other seasons remains unknown. Finally, for the 2018 season all catch data is sourced from the new TDB02 Docket-Book.

## 3. The TIB Docket-Book Data

The number of distinct vessel-symbols and seller-names associated with the 52,357 TIB catch records identified in the previous section is 1,278 and 2,433 respectively. However these numbers are inflated due to different spellings and mistakes often associated with a single vessel-symbol or seller-name. Attempts have been made to correct these names, and as a result the number of distinct vessel-symbols and seller-names has been reduced by nearly half, to 767 and 1,149 respectively. However, the percentage of all records (and total catch) without a vessel-symbol remains high at 68% (and 71% respectively). On the other hand, only 1.5% of all records (and 3.6% of the total catch) have no associated seller-name.

The frequency of the fishing methods associated with all Record Nos is shown in Table.2. Just over 40% of all records, and 39% of the total catch, are associated with hookah-diving, while free diving and lamp fishing are associated with 27% and 4.9% of the total catch respectively. Smaller amounts of the catch are also associated with handlining and trolling, and for around 2.5% of all records the catch is associated with some combination of these five fishing methods. However, the catch method for 12% of all catch records (and 26% of the total catch) remains unknown.

The distribution of all Record Nos (and catch) across each of the 21 TIB areas (shown in Figure 2) is given in Table 3. Around 42% of the records and slightly over a quarter (27%) of the catch have come from the Thursday Island region, with another 16% and 10% of the total catch coming from the Mabuiag and Badu regions respectively. Eleven of the 21 regions each account for less than one-percent of the total catch over all seasons (and only 2.4% in total). However, across all records the region fished remains unknown (i.e. not recorded) for 8.5% of all records (and 21% of the total catch). However, as noted by TSRL-RAG23 in May 2018, the

Table 2. Number of TIB catch records (and associated catch in kilograms) by fishing method.

| METHOD | N-recs | % | Catch | % |
|---|---|---|---|---|
| HOOKAH DIVING | 20974 | 40.1% | 1,111,117 | 39.0% |
| FREE DIVING | 18633 | 35.6% | 772,128 | 27.1% |
| UNKNOWN | 6495 | 12.4% | 736,115 | 25.8% |
| LAMP FISHING | 4903 | 9.37% | 139,958 | 4.91% |
| FREE DIVING-LAMP FISHING | 493 | 0.94% | 30,698 | 1.08% |
| FREE DIVING-HOOKAH DIVING | 260 | 0.50% | 27,089 | 0.95% |
| DIVING UNSPECIFIED | 214 | 0.41% | 15,897 | 0.56% |
| HANDLINING-FREE DIVING | 141 | 0.27% | 7,182 | 0.25% |
| HOOKAH DIVING-LAMP FISHING | 37 | 0.07% | 3,422 | 0.12% |
| TROLLING-FREE DIVING | 44 | 0.084% | 1,293 | 0.045% |
| HANDLINING | 33 | 0.063% | 842 | 0.030% |
| UNKNOWN-HOOKAH DIVING | 18 | 0.034% | 933 | 0.033% |
| FREE DIVING-HOOKAH DIVING-LAMP FISHING | 12 | 0.023% | 1,567 | 0.055% |
| HANDLINING-TROLLING-FREE DIVING | 18 | 0.034% | 561 | 0.020% |
| UNKNOWN-FREE DIVING | 13 | 0.025% | 419 | 0.015% |
| FREE DIVING-UNKNOWN | 12 | 0.023% | 659 | 0.023% |
| HOOKAH DIVING-UNKNOWN | 3 | 0.006% | 284 | 0.010% |
| UNKNOWN-FREE DIVING-LAMP FISHING | 3 | 0.006% | 228 | 0.008% |
| UNKNOWN-LAMP FISHING | 3 | 0.006% | 49 | 0.002% |
| TROLLING | 3 | 0.006% | 202 | 0.007% |
| LAMP FISHING-FREE DIVING | 1 | 0.002% | 53 | 0.002% |
| FREE DIVING-TROLLING | 3 | 0.006% | 51 | 0.002% |
| DIVING UNSPECIFIED-LAMP FISHING | 1 | 0.002% | 32 | 0.001% |
| UNKNOWN-FREE DIVING-HOOKAH DIVING | 1 | 0.002% | 18 | 0.001% |
| HANDLINING-TROLLING | 2 | 0.004% | 22 | 0.001% |
| TROLLING-DIVING UNSPECIFIED | 2 | 0.004% | 146 | 0.005% |
| HANDLINING-FREE DIVING-UNKNOWN | 2 | 0.004% | 30 | 0.001% |
| FREE DIVING-HANDLINING | 1 | 0.002% | 13 | 0.000% |
| ROD AND REELING-FREE DIVING | 1 | 0.002% | 30 | 0.001% |
| HANDLINING-DIVING UNSPECIFIED | 1 | 0.002% | 2 | 0.000% |
| Total | 52,327 | 1 | 2,851,041 | 1 |

Area fished information recorded on the TDB02 docket-book during the 2018 season did not align with knowledge of the main catch regions that season. This discrepancy raised the likelihood that the Area fished information recorded on the TIB Docket-Book records may not be correct in many instances. One possible explanation offered was that it may relate to where the catch was sold instead of where the catch was made. This may account for the high proportion of the catch recorded in the Thursday Island area.

The number of recorded days-fished associated with the above TIB catch records (c.f. Table 4) varies between 1 and 20 days, though is only one, two or three days for 74%, 6.4% and 3.2% of all catch records respectively. The days-fished remains unknown (i.e. not recorded) for 12.4% of these records (but for 26% of the total catch).

Finally, the number of crew recorded on the docket-books varies between 1 and 14 (c.f. Table 5), though is only numbers one or two for 58% and 27% of records respectively. The number of crew remains unknown for 13% of all records (and 28% of the total catch).

The seasonal percentage of the both the number of TIB catch records and total TIB catch for the various levels (a) fishing method, (b) area fished, (c) days fished and (d) number of crew are shown in Figure 3. The seasonal percent of blank (unknown) levels for each data field are

Figure 2. Spatial structure of the TIB data.

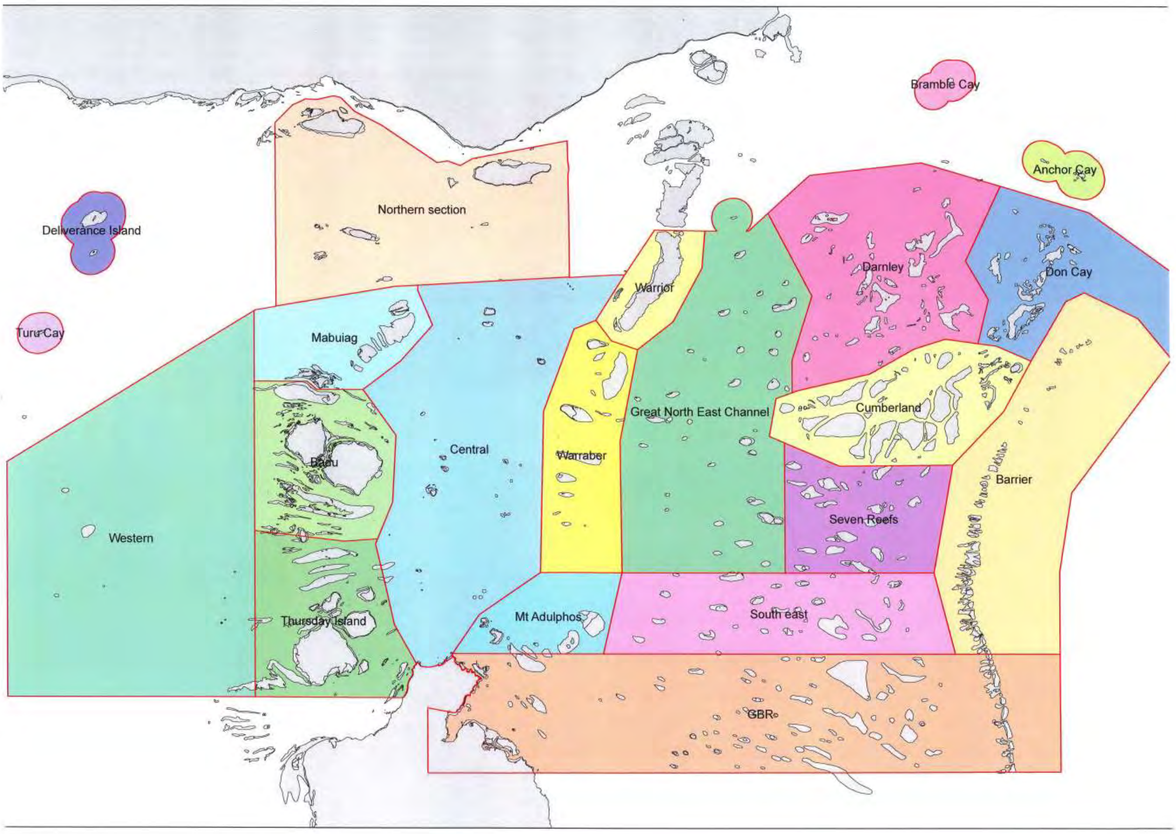



Table 3. Number of TIB records (and associated catch in kilograms) by region.

| Area | Area-Name | N-recs | % | Catch | % |
|---|---|---|---|---|---|
| 9 | Thursday Island | 21820 | 41.70% | 776,711 | 27.24% |
| 0 | Unknown | 4471 | 8.54% | 585,767 | 20.55% |
| 7 | Mabuiag | 6177 | 11.81% | 468,239 | 16.42% |
| 8 | Badu | 5910 | 11.30% | 293,125 | 10.28% |
| 12 | Warraber | 4310 | 8.24% | 197,039 | 6.91% |
| 11 | Warrior | 3155 | 6.03% | 175,133 | 6.14% |
| 14 | Great NE Channel | 2040 | 3.90% | 103,804 | 3.64% |
| 13 | Mt Adolphus | 698 | 1.3% | 54,817 | 1.9% |
| 17 | Cumberland | 818 | 1.56% | 45,153 | 1.58% |
| 16 | Darnley | 1269 | 2.4% | 44,049 | 1.5% |
| 10 | Central | 763 | 1.46% | 39,201 | 1.37% |
| 3 | Northern Section | 269 | 0.51% | 28,325 | 0.99% |
| 1 | Turu Cay | 248 | 0.47% | 13,569 | 0.48% |
| 15 | South East | 118 | 0.23% | 10,947 | 0.38% |
| 21 | GBR | 155 | 0.30% | 10,083 | 0.35% |
| 4 | Bramble Cay | 19 | 0.04% | 1,481 | 0.05% |
| 2 | Deliverance Island | 29 | 0.06% | 1,348 | 0.05% |
| 6 | Western | 21 | 0.04% | 1,078 | 0.04% |
| 18 | Seven Reefs | 8 | 0.02% | 475 | 0.02% |
| 20 | Barrier | 10 | 0.02% | 345 | 0.01% |
| 5 | Anchor Cay | 9 | 0.02% | 238 | 0.01% |
| 19 | Don Cay | 6 | 0.01% | 189 | 0.01% |
| Total | | 52,323 | 1 | 2,851,116 | 1 |

Table 4. Number of TIB records (and associated catch in kilograms) by the number of days fished as recorded on docket-books.

| Days | N-recs | % | Catch | % |
|---|---|---|---|---|
| 1 | 38,809 | 74.2% | 1,421,609 | 49.9% |
| Unknown | 6,509 | 12.4% | 747,479 | 26.2% |
| 2 | 3,350 | 6.4% | 213,000 | 7.5% |
| 3 | 1,686 | 3.2% | 145,597 | 5.1% |
| 4 | 756 | 1.4% | 89,535 | 3.1% |
| 5 | 585 | 1.1% | 87,664 | 3.1% |
| 6 | 195 | 0.4% | 42,048 | 1.5% |
| 7 | 176 | 0.3% | 36,776 | 1.3% |
| 8 | 97 | 0.2% | 27,252 | 1.0% |
| 9 | 72 | 0.1% | 21,032 | 0.7% |
| 10 | 32 | 0.1% | 7,306 | 0.3% |
| 11 | 20 | 0.0% | 6,792 | 0.2% |
| 13 | 8 | 0.0% | 2,086 | 0.1% |
| 14 | 13 | 0.0% | 1,329 | 0.0% |
| 12 | 8 | 0.0% | 768 | 0.0% |
| 16 | 3 | 0.0% | 524 | 0.0% |
| 15 | 2 | 0.0% | 192 | 0.0% |
| 17 | 2 | 0.0% | 109 | 0.0% |
| 20 | 1 | 0.0% | 18 | 0.0% |
| | 52,324 | 100.0% | 2,851,116 | 100.0% |

Table 5. Number of TIB records (and associated catch in kilograms) by the number of crew as recorded on docket-books.

| Crew | N-recs | % | Catch | % |
|---|---|---|---|---|
| 1 | 30,405 | 58.1% | 1,211,089 | 42.5% |
| Unknown | 6,596 | 12.6% | 793,554 | 27.8% |
| 2 | 14,133 | 27.0% | 772,013 | 27.1% |
| 3 | 998 | 1.9% | 57,758 | 2.0% |
| 4 | 140 | 0.3% | 7,536 | 0.3% |
| 6 | 7 | 0.0% | 3,927 | 0.1% |
| 5 | 20 | 0.0% | 3,597 | 0.1% |
| 8 | 7 | 0.0% | 1,096 | 0.0% |
| 7 | 7 | 0.0% | 285 | 0.0% |
| 12 | 2 | 0.0% | 99 | 0.0% |
| 10 | 3 | 0.0% | 77 | 0.0% |
| 9 | 3 | 0.0% | 41 | 0.0% |
| 14 | 1 | 0.0% | 37 | 0.0% |
| 11 | 1 | 0.0% | 9 | 0.0% |
| | 52,323 | 100.0% | 2,851,116 | 100.0% |

also shown. Between 2012 and 2016 there was a significant increase in the proportion of the seasonal catch for which the information relating to these four effort variables remains unknown, and this lack of information impedes the ability to construct indices of resource abundance that represent the distribution of lobsters across the TIB fishery. While this situation has improved in recent seasons, nevertheless there is still room for improving the information recorded on the TDB-02 docket-book (e.g. the area fished and related effort information was still not completed for around 20% of records in 2017 and 2018, cf. Figures 3a,b).

Figure 3a. Seasonal percent of (1) number of TIB catch records and (2) total TIB catch for the various levels of: (a) fishing method, (b) area fished in the data. The percent of the annual catch for which each data field was not completed (and therefore remains unknown) is also shown.

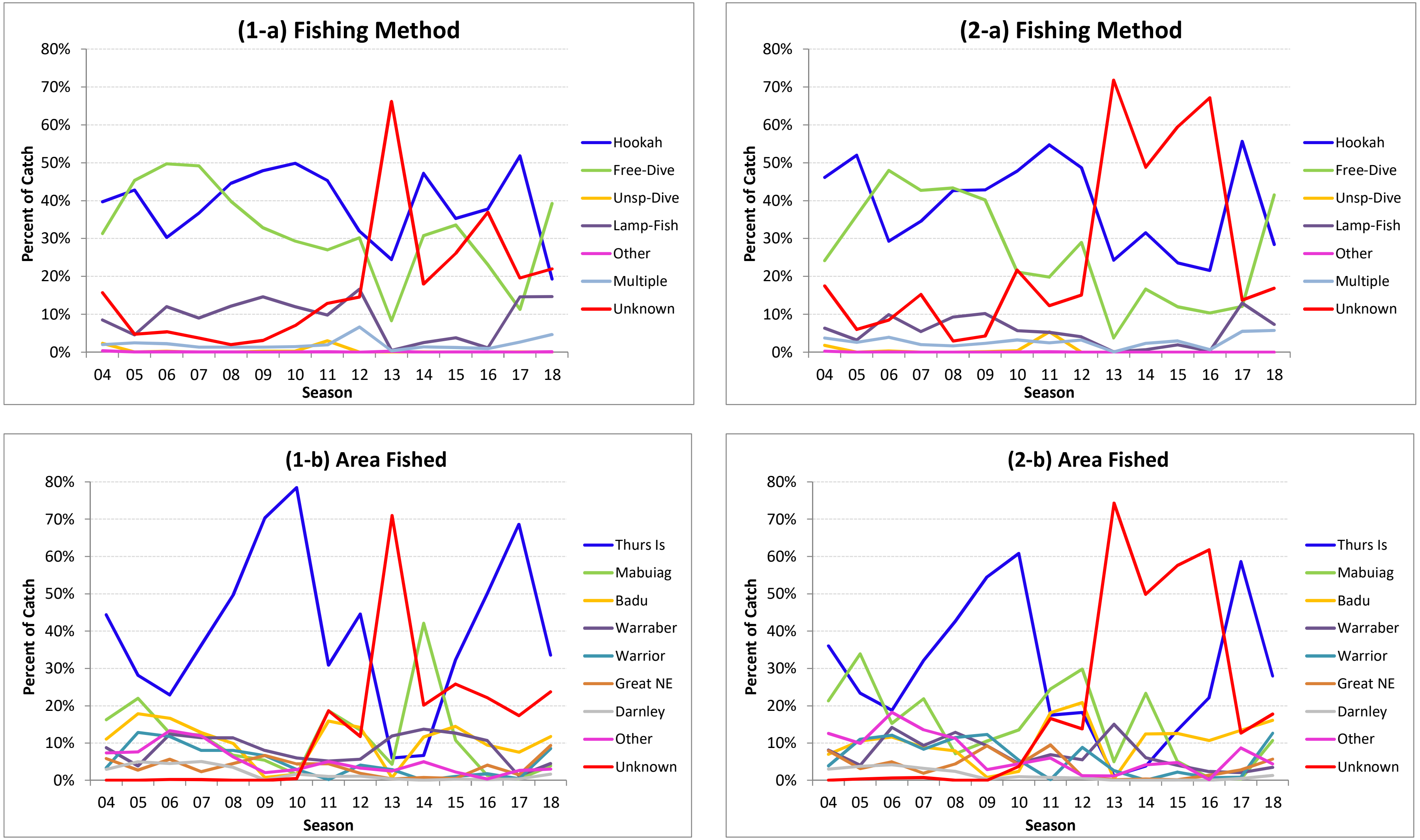
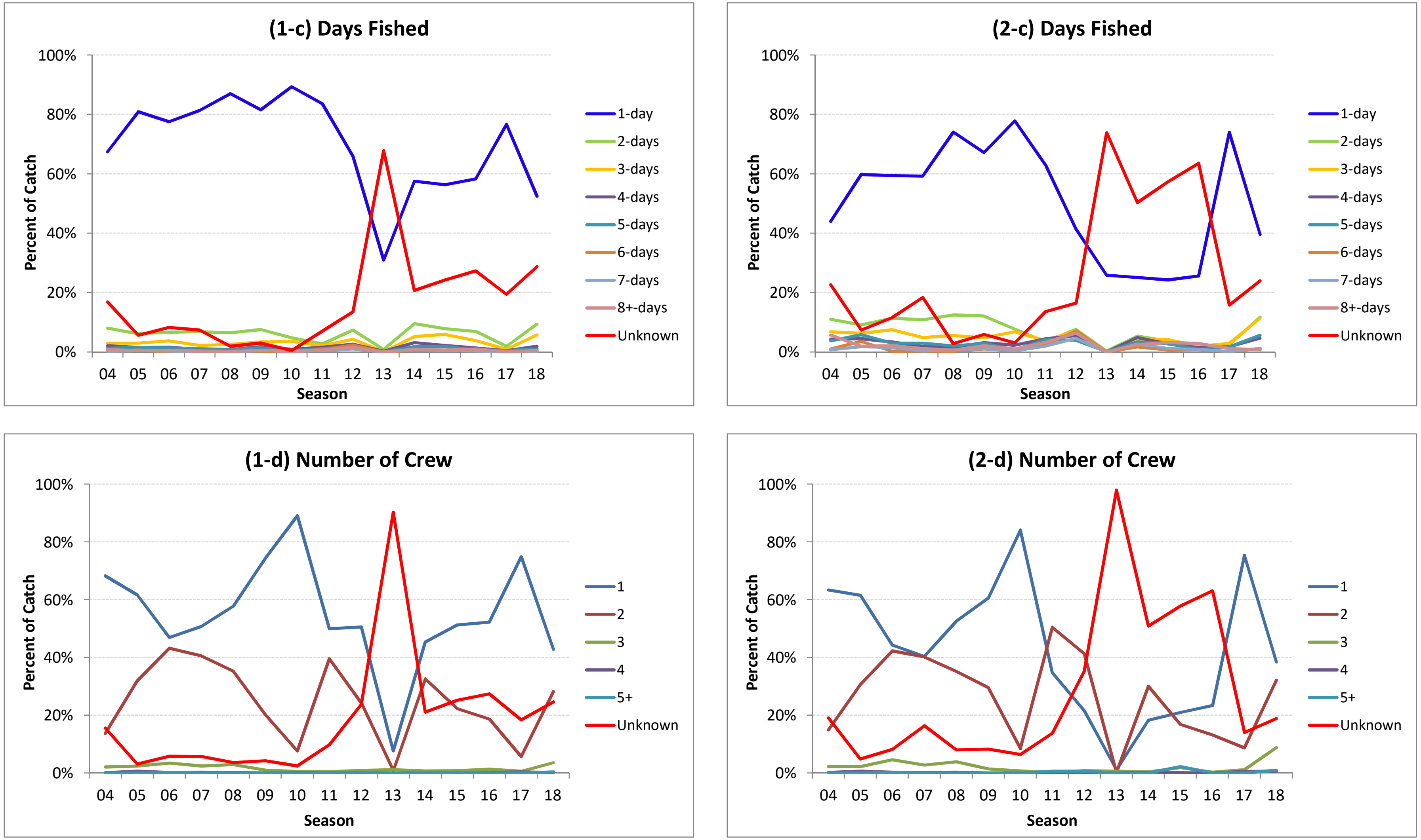


Figure 3b. Annual percent of (1) number of TIB catch records and (2) total TIB catch for the various levels of: (c) days fished and (d) number of crew. The percent of the annual catch for which each data field was not completed (and therefore remains unknown) is also shown.



## 3. Selection of data used for CPUE analysis

Each catch record in the TIB data is associated with a Record-No, and the structure of the Docket-Book would seem to indicate that there should be a unique Record-No for each vessel, date and seller-name. However, investigation of the data indicates that there are often multiple Record-Nos associated for a given vessel, date and seller-name. The reason for these multiple records remains unknown but may be due to incorrect recording of dates, etc. In order to identity an appropriate data structure for analysis, the following procedure was adopted to filter the data:

1. The TIB data was aggregated over vessel-symbol, date and seller-name. Where the vessel-symbol or seller-name was null these fields were set to 'Unknown';
2. Only those records where the first fishing method listed in Table 2 was either 'Hookah diving', 'Free diving' or 'Lamp fishing' were selected. This resulted in a total of 43,773 aggregate records (hence-forth known as GLM records);
3. Only those GLM records having a unique Record-No were selected for analysis – accounting for 42,308 (96.7%) of the GLM records identified in the previous step. It was assumed that where the vessel or seller were unknown, that selection of only those GLM records having a unique Record-No limited the GLM records chosen to those associated with a single vessel and a single seller;
4. An additional check was made to ensure that the number of days fished, the number of crew on the boat, the fishing method and the area fished was unique for each Record-No. This was done to help eliminate data errors. Five records were eliminated for having two methods each;
5. Finally, GLM records were also deleted where either the number of days fished was not recorded (1562), the area fished was not recorded (810), the record pertained to the TVH logbook data (704) as the structure of the data for these records was different, or the weight of the catch was zero (26) or greater than 1000 kg (17);
6. Finally, the records for the 2013 season were also deleted due to the small number of records for this season (47) compared to all other seasons (between 1,024 and 5,585). The small number for 2013 was due to the fact that many of the fields on the Docket-Book were left blank.
7. This process resulted in 39,271 GLM records being created and selected.

The number of GLM records, and associated nominal CPUE, within each season, month, quarter and TIB area and the distribution of records per fishing method, days-fished and the percent of the catch which are tailed lobsters are shown in Tables 6a&b (and for each 2-way combination of the season, month and area effects in Appendix B). Due to the small number of records in some TIB areas, these records were combined with the records in an adjacent area so that the minimum number of records in any area was more than 200. This resulted in twelve areas to be used as spatial effects in the GLM analysis. Furthermore, for all records where more than one fishing method was used the fishing method was termed Mixed. Consequently, only four types of fishing methods were in the data. There were also 1,005 distinct seller-names (unknown for only31 records) and 692 distinct vessels (but unknown for 68% of all records).

The substantive decline in the number of Records-Nos since 2010 has been noted earlier, with the average number of catch records per season decreasing from 3,898 between 2004 to 2010 to only 1,518 between 2011 and 2016. However, this situation improved substantially during 2017 with the greater use of the TDB01-Docket-Book when the number of records selected for the GLM analysis again exceeded 2,000 and has remained near this level during the shorter 2018 season.

Table 6a. Number of GLM records within each season, month and quarter and associated nominal catch rate.

| Season | N-Recs | CPUE |
|---|---|---|
| 2004 | 2,898 | 33.1 |
| 2005 | 5,585 | 39.3 |
| 2006 | 3,263 | 25.7 |
| 2007 | 5,330 | 31.1 |
| 2008 | 4,326 | 30.1 |
| 2009 | 3,240 | 27.5 |
| 2010 | 2,641 | 30.9 |
| 2011 | 1,841 | 51.2 |
| 2012 | 1,024 | 42.2 |
| 2014 | 1,491 | 32.5 |
| 2015 | 1,721 | 24.1 |
| 2016 | 1,513 | 31.5 |
| 2017 | 2,457 | 26.6 |
| 2018 | 1,941 | 27.6 |
| Total | 39,271 | |

| Month | N-Recs | CPUE |
|---|---|---|
| 1 | 3531 | 27.5986 |
| 2 | 5578 | 35.2989 |
| 3 | 6385 | 36.0666 |
| 4 | 4524 | 36.1713 |
| 5 | 4300 | 34.4775 |
| 6 | 3834 | 34.0037 |
| 7 | 3716 | 32.1566 |
| 8 | 2611 | 30.7584 |
| 9 | 1831 | 27.2811 |
| 10 | 39 | 23.3836 |
| 11 | 7 | 21.73 |
| 12 | 2915 | 26.4867 |
| Total | 39,271 | |

| Qtr | N-Recs | CPUE |
|---|---|---|
| 1 | 15494 | 33.8604 |
| 2 | 12658 | 34.9394 |
| 3 | 8158 | 30.6149 |
| 4 | 2961 | 26.4346 |
| Total | 39,271 | |

Table 6b. Number of GLM records within each TIB area and distribution across each recorded fishing method and days-fished and the associated nominal catch rate.

| TIB-Area | GLM-Area | N-Recs |
|---|---|---|
| 1 | 6 | 92 |
| 2 | 6 | 22 |
| 3 | 6 | 209 |
| 4 | 16 | 15 |
| 5 | 16 | 9 |
| 6 | 6 | 16 |
| 7 | 7 | 4810 |
| 8 | 8 | 5042 |
| 9 | 9 | 18462 |
| 10 | 10 | 632 |
| 11 | 11 | 2432 |
| 12 | 12 | 3349 |
| 13 | 13 | 593 |
| 14 | 14 | 1641 |
| 15 | 15 | 108 |
| 16 | 16 | 953 |
| 17 | 17 | 733 |
| 18 | 15 | 8 |
| 19 | 16 | 4 |
| 20 | 15 | 10 |
| 21 | 15 | 131 |
| Total | | 39,271 |

| GLM-Area | N-Recs | CPUE |
|---|---|---|
| 6 | 339 | 44.2613 |
| 7 | 4810 | 41.7809 |
| 8 | 5042 | 30.9401 |
| 9 | 18462 | 31.1478 |
| 10 | 632 | 32.2396 |
| 11 | 2432 | 41.1091 |
| 12 | 3349 | 23.6417 |
| 13 | 593 | 47.6454 |
| 14 | 1641 | 31.4873 |
| 15 | 257 | 43.3771 |
| 16 | 981 | 30.9084 |
| 17 | 733 | 36.8099 |
| Total | 39,271 | |

| %-Tails | N-Recs | CPUE |
|---|---|---|
| <20% | 11,759 | 23.3 |
| 20-40% | 2,962 | 35.4 |
| 40-60% | 2,414 | 35.6 |
| 60-80% | 2,137 | 38.5 |
| >80% | 19,999 | 37.4 |
| Total | 39,271 | |

| Method | N-Recs | CPUE |
|---|---|---|
| FREE | 16255 | 31.4946 |
| HOOKAH | 18293 | 36.7398 |
| MIXED | 4723 | 23.4807 |
| Total | 39,271 | |

| Days | N-Recs | CPUE |
|---|---|---|
| 1 | 33,019 | 33.5 |
| 2 | 2,976 | 31.7 |
| 3 | 1,497 | 28.5 |
| 4 | 679 | 29.7 |
| 5 | 545 | 29.3 |
| 6 | 176 | 36.0 |
| 7 | 157 | 28.0 |
| 8 | 83 | 36.4 |
| 9 | 66 | 31.4 |
| 10 | 28 | 22.6 |
| 11 | 18 | 27.5 |
| 12 | 6 | 10.5 |
| 13 | 7 | 18.5 |
| 14 | 9 | 5.2 |
| 15 | 2 | 5.8 |
| 16 | 3 | 10.9 |
| Total | 39,271 | |

Unlike the TVH data where the measure of effort is hours-fished, the measure of effort for the TIB data is coarser, being days-fished. Furthermore, and as noted above, it has been assumed that each selected GLM record pertains to the catch and effort of a single fisher (or seller) during a given trip, i.e. it is assumed that the measure of effort (i.e. days fished) associated with each GLM record also pertains to the actual effort expended by that seller in obtaining the recorded catch. While the number of days fished for each Record-No in the GLM data is unique, there are instances nevertheless where for the same vessel, date and seller there are multiple Record-Nos where the number of days fished is different. Investigation of this issue undertaken with the AFMA data section indicated that the dates associated with these docket-book forms were most likely not correct (Campbell 2016a).

## 4. General Linear Model Analysis

As with the analysis of the TVH data in previous years, General Linear Models (GLM) were fitted to the TIB data selected in the previous section in order to standardise the CPUE to account for changes in the distribution of records across a number of effects (e.g. Season, Month, Area and Fishing-Method). As mentioned previously, the measure of effort for the TIB data was taken to be days-fished. The catch rate associated with each GLM record was then defined to be the mean weight of lobsters caught per day-fished, i.e.

$$CPUE = \frac{Whole\ \ Weight\ of\ landed\ lobsters}{Number\ of\ days\ fished}$$

In order to investigate the influence of the various effects on the catch rate associated with each GLM data record, and to help account for the possible misreporting of the Area fished on Docket-Book records (as noted by TSRL-RAG23 in May 2018), the following two models were fitted to the data records described in the previous section. All GLMs were weighted as described in Campbell (2018c).

Model-1: Main Effects (labelled Main in the remainder of this report)

*CPUE = Intercept + Season +Month +Method + Proportion-Tails + SOI + Moon-Phase*
/ distribution = gamma, link = log

Model-2: Main Effects + Area Effect (labelled Main+A in the remainder of this report)

*CPUE = Interc + Season +_Month + Area +Method+ Proportion-Tails + SOI + Moon-Phase*
/ distribution = gamma, link = log

where:

a) *Season* has 12 levels: 2004-2012, 2014-2018 (see below)
b) *Month* has 10 levels: December–to-September.
c) *Area* has the 12 levels as shown in Table 6b.
d) *Fishing-Method* has 4 levels: (1) Hookah, (2) Free Diving, (3) Lamp Fishing, and (4) Mixed methods
e) *Proportion*-Tails has 5 levels: (1) <20%, (2) 20-40%, (3) 40-60%, (4) 60-80%, and (5) ≥80%
f) *SOI* is the monthly value of the Southern Oscillation Index
g) *Moon-Phase* has 30 levels: the number of days after the last full moon.

All effects were fitted as categorical effects except for SOI which was fitted as a continuous cubic function.

Each of the above models were fitted to the TIB described in the previous section with the following filters: (a) the data for October and November were not included in the GLM due to the small number of records in each month (39 and 7 respectively), (b) the 75 data records where the number of days fished was greater than 9 were excluded as the mean catch rates for these records was substantially below those where the number of days fished was between 1 and 9 days, (c) the 512 records where the catch was less than 1.0 kg or greater than 300 kg as these could also be misreported catches or outliers. This left a total of 38,837 records.

Using the results from each GLM a seasonal abundance index was constructed based on the standardised CPUE calculated for each of the (Season, Month, Area) strata. As the standardised

-CPUE is taken as an index of the density of fish within each strata, an index of the abundance of lobsters across the fishery in each season and month is given by:

$$Index(season = s, month = m) = \frac{1}{\sum_{a=1}^{NA} Area_a} \sum_{a=1}^{NA} Area_a . stdCPUE(s, m, a)$$

where $Area_a$ is the spatial size of each of the *NA Area* effects included in the GLM. Finally, an index of abundance for each season can be obtained by taking the average across the *NM Month* indices in each season.

$$Index(season = s) = \frac{1}{NM} \sum_{m=1}^{NM} \left[ \frac{1}{\sum_{a=1}^{NA} Area_a} \sum_{a=1}^{NA} Area_a . stdCPUE(s, m, a) \right]$$

Finally, a relative annual abundance index, $B_s$, was calculated such that the mean index over all seasons equals 1, i.e.

$$B_s = \frac{Index(season = s)}{\frac{1}{NS} \sum_{i=1}^{NS} Index(season = i)}$$

For those models which do not included an interaction with the Season effect the relative abundance index, $B_s$, reduces to the simpler form:

$$B_s = \frac{\exp(S_s)}{\frac{1}{NS} \sum_{i=1}^{NS} \exp(S_i)}$$

where $S_i$ , *i=1, NS* are the parameters estimates relating to *NS Season* effects included in the model. In these situations the abundance is independent of the relative size of each *Area* effect included in the GLM.

No models including an interaction with the *Season**Area* interaction effect were fitted as 22% of the *Season *Area* strata have fewer than 10 records (with 12 having no data records, c.f. Appendix B) and construction of an abundance index from a model including a *Season*Area* interaction would entail the need to impute catch rates for those strata for which the number of records is zero or small (and, hence, maybe unrepresentative). While there was only three *Season*Month* strata having no data records (c.f. Appendix B), no models including an interaction with the *Season *Month* interaction effect were fitted due to the need to know the spatial extent occupied by lobsters within each TIB fishing region (required to construct the abundance index as explained above) and the related uncertainty noted in previous reports about the spatial size of each GLM-area.

Together with the two models described above, a second set of analyses was also undertaken where the Seller-Name (*Seller*) was also fitted as an additional effect to each of the models. To ensure that there was sufficient data for parameter estimation of each *Seller* effect only those sellers which had fished for three or more seasons and for which there were 30 or more data records where included in the analyses. This left a total of 32,360 records for 262 distinct Sellers. A summary of all models fitted in provided in Table 7.

Table 7. Summary of models fitted to the TIB data.

| Model | | # Fitted Parameters | # Seller Parameters | Records | AIC |
|---|---|---|---|---|---|
| 1 | Main Effects | 63 | 0 | 38,837 | 342,753 |
| 2 | Main Effects + Area | 74 | 0 | 38,837 | 346,966 |
| 3 | Model 1 + Seller-Name | 324 | 262 | 32,360 | 280,371 |
| 4 | Model 2 + Seller-Name | 335 | 262 | 32,360 | 282,956 |

## 5. Results and Abundance Indices

*(a) Standardising Effects*

Statistics for the Type 3 contrasts computed for each fitted effect indicated that each effect was highly significant. A comparison of relative influence of each level of the *Month*, *Area*, *Method*, *Proportion-Tails, SOI and Moon-Phase* effects for each model is shown in Figure 4. For each effect the values have been scaled so that the influence of each effect is relative to a selected reference level.

Relative CPUE between months is seen to increase at the start of the season from December to March (by 15-20% depending on the model) then remain fairly stable before declining during August before reaching a seasonal low during September (~15% less than at the start of the season).

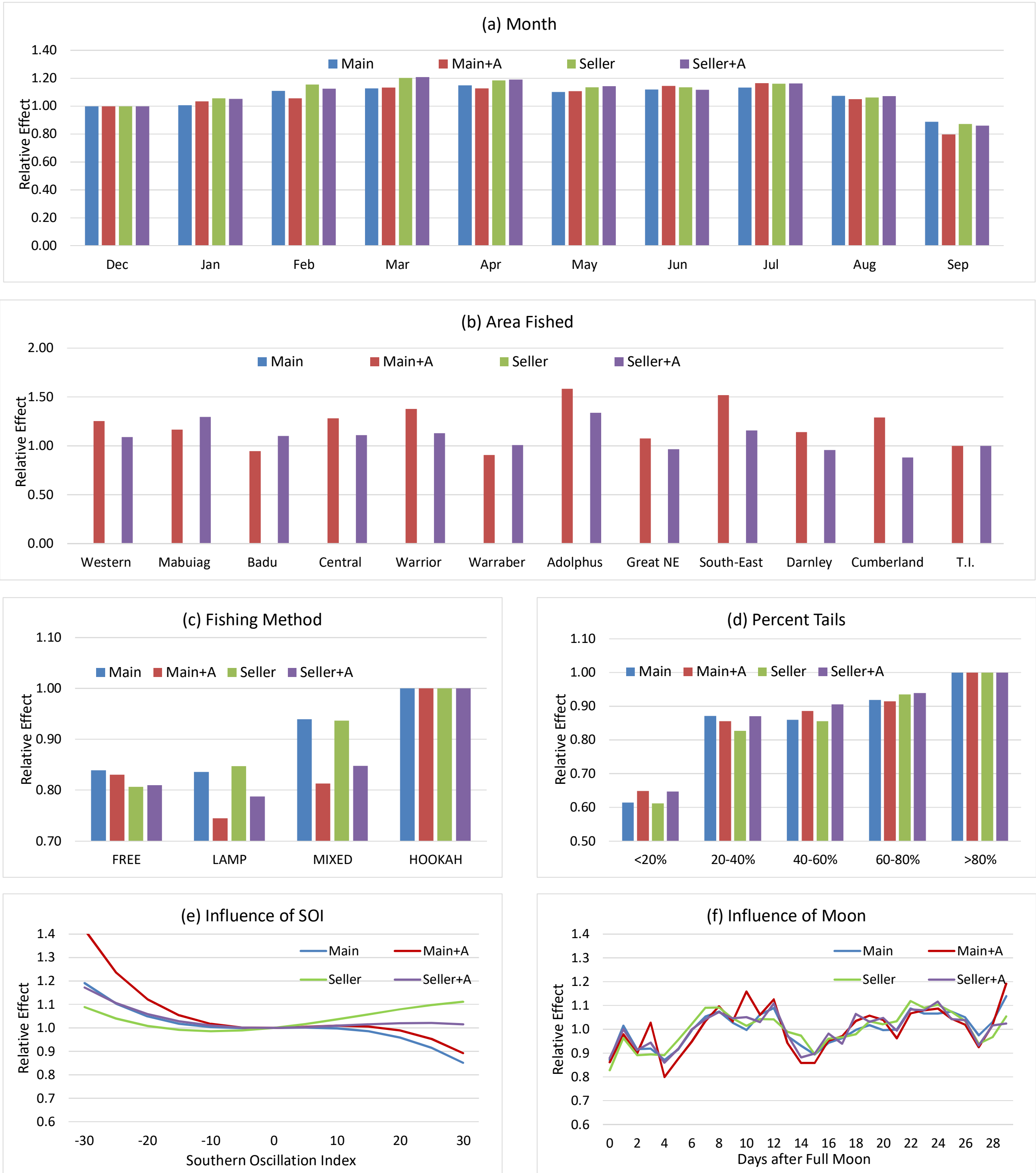
Relative CPUE varies considerably between the various areas included in the models. There is also considerable variation in the relative effect for a particular area between the different models. For example, for the *Main*-effects the relative CPUE's vary between 158% (for Adolphus) to 91% (for Warraber), while for the *Seller*-effects model, the relative CPUE's varies between 134% (again for Adolphus) to 88% (for Cumberland). However, the uncertainty over the meaning the Area-fished field needs to be taken into consideration.

The relative CPUE of each fishing method also shows some differences across all models, though are similar for the two sets of models with and without the *Area*-effect included. For the two models without the *Area*-effect included, the CPUE for hookah fishing is found to be around 22% higher than for free diving, 19% higher than for lamp fishing, and 7% higher than for mixed fishing. This latter result is to be expected if mixed fishing is a combination of the two other fishing methods.

Finally, the relative CPUE across all models is similar for each category of the proportion of the catch which is tails with the relative CPUE increasing as the *Proportion-Tails* increases in the catch. Across all models, the relative CPUE within each *Proportion-Tails* category is 63%, 86%, 88%, 93%and 100% respectively.

Of the two environmental effects, the results shown in Figure 4e indicate that high negative values of the SOI (i.e. strong El Nino conditions) tend to increase CPUE while the influence of high positive values of the SOI (i.e. strong La Nina conditions) is less clear. This result is different from that found when analysing the TVH data. However, there is a high level of uncertainty associated with these results as over the 175 months between January 2004 and July 2018 there have been only 3 months where the mean monthly value of the SOI has been

Figure 4. Comparison of relative influence of each level of the Month, Area, Method, Percent-Tails, SOI and Moon-Phase effects for each fitted model. Results are shown for all four model runs. Note, for each effect the values have been scaled so that the influence of each effect is relative to that of the last level of each effect (i.e, Month=December, Area=T.I., Method= Hookah, %-Tails= '>80%', and Moon-Phase=Mean over all phases).




less than -20 and 6 months where this value has been greater than 20, and between these values the influence of the SOI is seen to be relatively small. The influence of the Moon-Phase on CPUE, shown in Figure 4(f), is seen to be similar across all models, and while displaying a degree of variability indicates a bi-modal distribution across the days between successive full moons similar to that found with the TVH analysis. CPUE is lowest during days near a full and new moon, while CPUE is highest mid-way between these two phases (i.e. around the first and

Table 8. Relative abundance indices based on standardised CPUE data for the TIB fishery. Note, each index is scaled so that the mean of the index over the all seasons is equal to 1.

| Season | Nominal | Main+A | Main | Seller+A | Seller |
|---|---|---|---|---|---|
| 2004 | 0.98 | 0.85 | 0.90 | 0.93 | 0.94 |
| 2005 | 1.16 | 0.94 | 0.99 | 1.04 | 1.05 |
| 2006 | 0.82 | 0.74 | 0.78 | 0.78 | 0.78 |
| 2007 | 0.97 | 0.90 | 0.88 | 0.91 | 0.87 |
| 2008 | 0.95 | 0.85 | 0.85 | 0.85 | 0.83 |
| 2009 | 0.93 | 1.02 | 0.93 | 0.96 | 0.90 |
| 2010 | 0.98 | 1.01 | 0.95 | 1.05 | 0.99 |
| 2011 | 1.52 | 1.37 | 1.40 | 1.35 | 1.36 |
| 2012 | 1.11 | 1.13 | 1.21 | 1.22 | 1.26 |
| 2013 | | | | | |
| 2014 | 1.00 | 0.97 | 1.01 | 0.99 | 1.08 |
| 2015 | 0.76 | 0.88 | 0.85 | 0.89 | 0.92 |
| 2016 | 1.09 | 1.22 | 1.14 | 1.19 | 1.15 |
| 2017 | 0.82 | 1.12 | 0.99 | 0.95 | 0.91 |
| 2018 | 0.89 | 1.00 | 1.10 | 0.89 | 0.94 |
| Mean | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

Figure 5. Relative indices of resource availability based on each the models fitted to the catch and effort data for the TIB fishery.

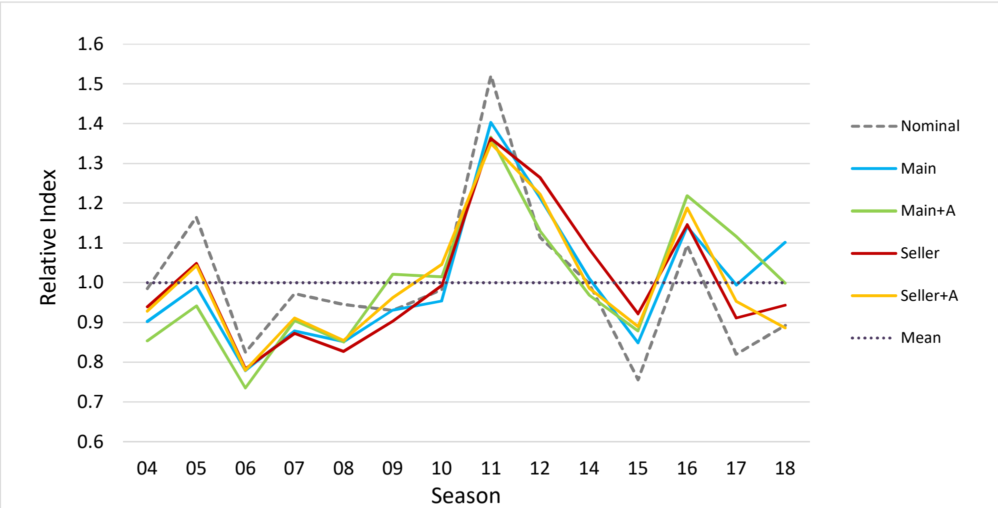
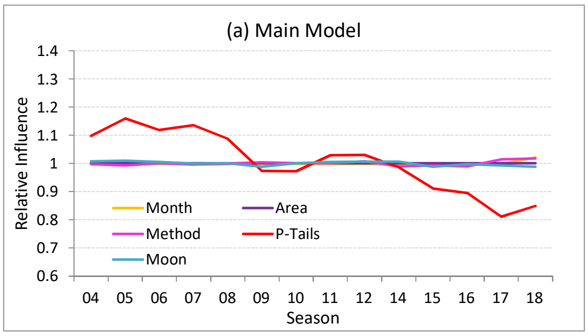



Figure 6. Annual influence of the fixed effects fitted to (a) the Main-Effects model and (b) the Seller-Effects model.



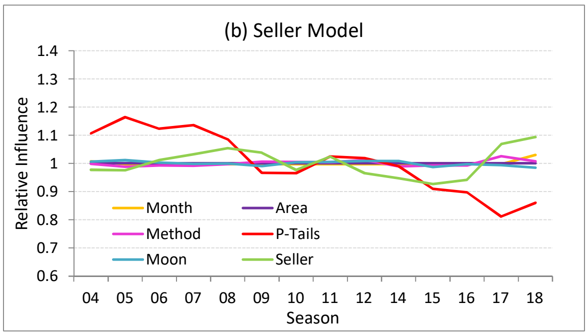
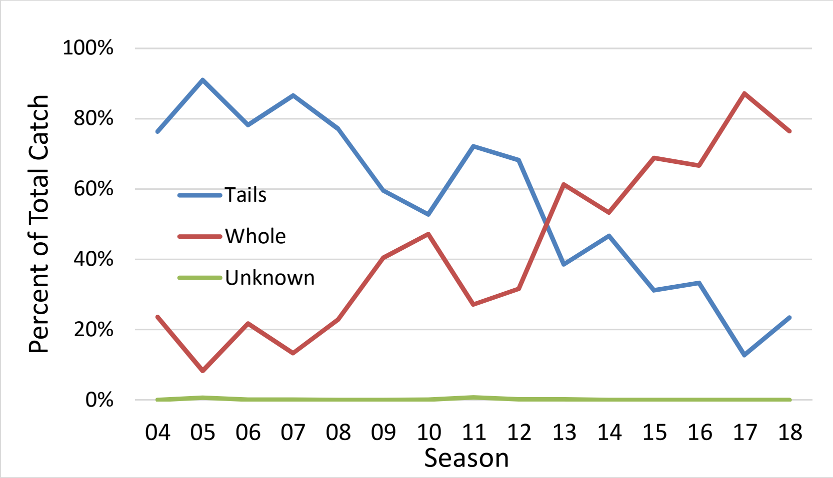



Figure 7.Percent of total annual catch (whole weight) by processed form.




last quarters). Average across all models, during this latter periods CPUE is around 30% higher than during the periods of lowest CPUE.

*(b) Annual Abundance Indices*

The seasonal abundance indices based on each of the four GLM models listed in the previous section are listed and displayed and in Table 8 and Figure 6 respectively. Relative to the nominal index, each of the standardised indices displays a number of substantive shifts, generally being lower than the nominal index over the first half of the time-series and higher than the nominal index during the second half (i.e. since 2012).

The reasons for these changes can be investigated using the seasonal influence of each main effect which is shown in Figure 7 for the Main and Seller models. The influence on the seasonal index is seen to be greatest for the *Proportion-Tails* effect, and the decreasing trend observed over time is correlated with the shift from the catch being predominantly tails to now being predominantly whole lobsters (c.f. Figure 7), with the latter process type decreasing CPUE (c.f. Figure 4(d)). The other effect having a substantive influence on the annual index is the *Seller* effect, and while displaying a variable influence over time the influence of this effect has increased in recent seasons resulting in an increase in catch rates. This indicates that there has been an increase in the relative fishing efficiency of *Sellers* in recent seasons, which when accounted for in the standardising model leads to a decrease in the standardised CPUE. The influence of the *Seller* effect in recent seasons therefore explains the divergence seen between the standardised indices based on the Main and Seller models during this period. The annual influence of the other effects included in the standardising models is seen to be negligible, likely due to the fact that there has been no systematic shift in the relative degree of fishing within each level of these effects over time. For example, the proportion of fishing during each level of Moon-phase is likely to have remained unchanged over time (likely being relatively equal each season).

Using the Akaike Information Criteria (AIC) as a measure to select the relative quality of the different statistical models fitted to a given set of data (where a lower value is better), then based on the results shown in Table 7, and across the two sets of models (i.e. Main vs Seller), the models without the *Area* effect included are found to provide a better fit to the data. Although using an *Area* effect would usually be seen as a good explanatory variable to account for changes in CPUE due to the spatial variation in the distribution of the lobster resource, this otherwise unintuitive result may be influenced by the poor quality of the data related to the Area fished recorded on the TIB docket-books. Furthermore, and while not shown in Table 7, the AIC measure also indicates that between the two models with and without the *Seller*-effect included and fitted to the same set of data as Model 3 (i.e. 32,360 records) that the model including the *Seller*-effect provides the better fit (AIC=280,371 vs 287,500). Based on these observations, Model 3 is therefore seen as the preferred model.

## 6. Comparison with other indices

A comparison of the TIB abundance indices with two of the preferred indices based on the standardised CPUE from the TVH fishery is shown in Figure 8 while the Pearson correlation, ρ, between each of these indices is shown in Table 9. A number of differences are seen between each set of indices. In particular, the standardised TIB indices each display a considerably flatter trend over time than the TVH indices. Despite this, the peaks and troughs in each of the TIB and TVH indices generally coincide. For example, local maximum occur for the 2005, 2011 and 2016 seasons while local minimum occur for the 2006, 2009, 2015 and 2017 seasons. This similarity is also reflected in the relatively high correlation (ρ =0.8) between the TIB index (*Seller*) and the two TVH indices. As both the TIB and TVH fisheries are fishing the same resource, this result should not be unexpected. The reasons for the flatter trend in the TIB indices remain uncertain and warrants further investigation, but may be due to the nature of the data collected from this fishery, in particular the courser scale measure of effort collected from the TIB fishery (day) in comparison to that collected in the TVH fishery (hours). There is also a problem with the substantive amount of data which is not included in the analyses for the TIB fisher in some seasons, and its more limited spatial extent. Some form of hyper-stability in catch rates in the TIB-sector also cannot be ruled out.

Figure 8. Comparison of the selected TIB and TVH resource indices.

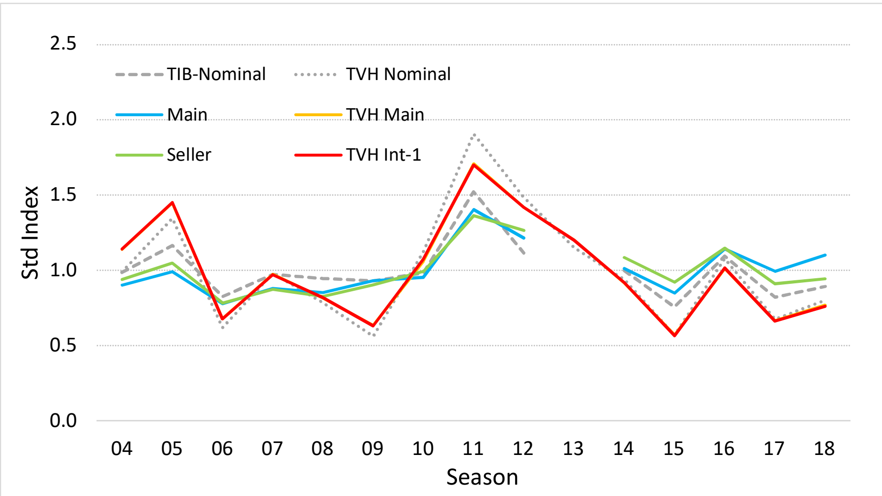



Table 9. Pearson correlation between the various TIB and TVH-based indices.

| Model | TVH-Main | TVH-Int1 |
|---|---|---|
| Main | 0.71 | 0.70 |
| Main+A | 0.54 | 0.53 |
| Seller | 0.80 | 0.80 |
| Seller+A | 0.80 | 0.80 |

## 7. Concluding Remarks

For the Torres Strait rock lobster fishery there are currently two sources of catch and effort data, those for the TVH and TIB sectors. The TRL04 Logbook data from the TVH sector is believed to provide a relatively complete and good source of catch and effort data for this sector (e.g. Campbell eta al, 2018). Improvements in compliance to ensure that all fields in the Logbook are completed (e.g. area fished and hours fished) would improve the utility of these data. Also, a better recording of the locations of the fishing effort (i.e. at the tender level) would also improve the accuracy of the data for standardising catch rates. On the other hand, the data for the TIB sector is less complete and the measure of effort (days fished) is less accurate and incomplete in many instances. However, given the potential for this sector to grow in importance in future years there is a need to assess the utility of these data to provide a useful index of resource abundance.

The results presented above indicate that while the TIB-based indices have the potential to capture the major trends stock abundance, they likely lack the detail required to track finer inter-annual trends in abundance. There are several reasons for this outcome. In particular, the measures of catch and effort in the TIB data are coarser (trip-based) compared to the tender-hours based data for the TVH data. Indeed, for the TIB data it remains unknown how many hours per trip fishing actually occurred and whether there are differences between the different sellers and trends over the years. Also of concern is the likely lack of accuracy of the data related to the Area fished being recorded in the docket books, as this is likely to be highly influential variable in helping to account for the annual variability in catch rates across the fishery.

Finally, it has been noted that either the Docket-Book or many of the fields in the Docket-Book were not completed in recent seasons, though there were improvements in 2017 and 2018. With the introduction of the new Torres Strait Catch Disposal Record (TDB02, shown in Appendix A) it is hoped that the improvements seen in data recording will continue. While the recording of several data fields (e.g. Fisher Name, Fisher Type, Boat Symbol, and catch details) will be mandatory in the new form, it is also essential that the other fields in the voluntary sector of the form (e.g. detailing fishing effort and methods) are completed if the required information is to be available for standardising the TIB catch and effort data. As with the TVH data, continued effort needs to be placed on ensuring the completeness and accuracy of these data if they are to be used on a continuing basis.

## References

Campbell, R.A., 2016a. Data issues pertaining to the Torres Strait rock lobster fishery – discussions with AFMA. Information paper presented to the 18th meeting of the Torres Strait Rock Lobster Resource Assessment Group, held 2-3 August 2016, Thursday Island.

Campbell, R.A., 2016b. Separating TIB, TVH and Processor catch records from Docket-Book Data. Report to AFMA.

Campbell, R.A, Dennis, D., Plaganyi, E., Deng, R., 2017. Use of TIB Logbook Data to construct an Annual Abundance Index for Torres Strait Rock Lobster – 2017 Update. Information paper presented to the 21st meeting of the Torres Strait Rock Lobster Resource Assessment Group, held 12-13 December 2017, Cairns.

Campbell, R.A., Pease, D. 2017. Separating TIB, TVH and Processor catch records from Docket-Book Data. Report to AFMA – 2017 Update. Information paper to be presented to the 21st meeting of the Torres Strait Rock Lobster Resource Assessment Group, held 12-13 December 2017, Cairns.

Campbell, R.A, Plaganyi, E., Deng, R., 2018. Use of TVH Logbook Data to construct an Annual Abundance Index for Torres Strait Rock Lobster – 2018 Update. Information paper to be presented to the 24th meeting of the Torres Strait Rock Lobster Resource Assessment Group, held 18-19 October 2018, Cairns.

Appendix A (i). The old Buyers and Processors Docket Book (TDB01) used in the TIB sector of the Torres Strait rock lobster fishery.

**Torres Strait Seafood Buyers and Processors Docket Book**

**RECIPIENT CREATED TAX INVOICE**

**FOR** Name:..........................................................................................

Address:..........................................................................................

..........................................................................................

A.B.N.:..................................Lic. No. ..................................

| | | | | | |
|---|---|---|---|---|---|
| Seller: | | | | **Book No.** | **Page No.** |
| Seller's ABN: | | Seller's Licence No. | | | |
| Seller's Address: | | | | Date: | |

**Fishing effort and boat details – Traditional Inhabitant Boat (TIB) only**

| | | | |
|---|---|---|---|
| Boat symbol: | | No. of divers/fishers: | |
| Days fishing: | | Area fished: From map (write no. of area most fished) | |

Methods used: (tick box, use more than one if needed)
☐ Hookah (MDH) ☐ Handline (LHL) ☐ Drop line (LDR)
☐ Free dive (MDF) ☐ Rod and reel (LRR) ☐ Other– specify
☐ Lamp fishing (MLF) ☐ Troll (LTL)

**Non Traditional Inhabitant Boat (TIB) fishers & buyers of PNG & east coast product only**

Region Fished: (tick box) ☐ Torres Strait ☐ East Coast Queensland ☐ Papua New Guinea

Has the seller recorded their catches elsewhere?: (tick box) ☐ YES (please indicate) → ☐ TRL04 Logbook ☐ TSF01 Logbook ☐ Other →
☐ No

**Details of catch being sold**

| Species | Processing Code | Grade | Kg | $/Kg (SEEN BY AFMA (OPTIONAL)) | $/Kg (NOT SEEN BY AFMA) | Amount (NOT SEEN BY AFMA) |
|---|---|---|---|---|---|---|
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| Completed by: | | | | | Subtotal | |
| Signature: | | | | | GST | |
| Payment received: | | | | | **TOTAL** | |

| | | |
|---|---|---|
| Australian Fisheries Management Authority<br>PO Box 376<br>Thursday Island QLD 4875 | **For assistance**<br>Phone: (07) 4069 1990<br>Fax: (07) 4069 1277 | WHITE COPY: **Fisher** (seller)<br>YELLOW COPY: **AFMA**<br>PINK COPY: **Buyer** (you) |

Appendix A (ii). The new Torres Strait Catch Disposal Record (TDB02) to be used in the TIB sector of the Torres Strait rock lobster fishery.

Australian Fisheries Management Authority
Box 7051
Canberra Mail Centre ACT
2610

| CDR No. | 40 | Page No. | 34 |
|---|---|---|---|

## Torres Strait Catch Disposal Record TDB02

**PART A - MANDATORY**

| Receiver Details | | | | | |
|---|---|---|---|---|---|
| Fish Receiver Name | | Fish Receiver Licence No. | | Date | |
| Fish Receiver Address | | | | | |

| Fisher Details | | | |
|---|---|---|---|
| Fisher Name | | Fishing Licence Number | |
| Fisher Type (Circle One) | TIB TVH Sunset | Boat Symbol | |

| Logbook Number and Page Numbers this catch relates to | Logbook Number | & | Page Number(s) | |
|---|---|---|---|---|

| Details of Catch | | | | | |
|---|---|---|---|---|---|
| | Part or Whole of Catch? (Circle One) | | Part | Whole | |
| Species | Processing Code | Grade | Weight | $/kg | $ Total |
| | | | | Not Entered in Catchwise | Not Entered in Catchwise |
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| TOTAL (Optional) | | | | | |

| Signature of Receiver | | Received by (Name) | |
|---|---|---|---|

**PART B - VOLUNTARY/OPTIONAL**

| Fishing Effort and Area (Voluntary) | | | |
|---|---|---|---|
| Number of Fishers | | Number of Days | |
| Area Fished | | Start and End Dates | |

| Fishing Method (Voluntary) | | | | | |
|---|---|---|---|---|---|
| Hookah (MDH) | | Handline (LHL) | | Drop Line (LDL) | |
| Free Dive (MDF) | | Rod and Reel (LRR) | | Other | |
| Lamp Fishing (MLF) | | Troll (LTL) | | (Specify) | |

| Tax Receipt Details (Optional) | | | |
|---|---|---|---|
| Fisher ABN | | Fisher Address | |
| Receiver ABN | | Receiver Address | |
| Invoice Total ($) | | GST ($) | |
| Signature of Fisher | | Date | |

White Copy Must go to AFMA within 3 days of unload
Pink Copy Fisher to Retain
Green Copy Remains in this logbook (Receiver copy)

**For assistance please contact AFMA Direct 1300 723 621**

Appendix B (i). Number of GLM data records, total number of days fished, total catch weight, and associated CPUE in each Season*Area strata. Note, strata with less than 10 records are shaded (dark shading where number is zero) and nominal CPUE is only shown for strata where the number of the days fished is 5 or greater.

(a) Number of TIB RECORDS

| | | Season | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Area | Area | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | Total |
| Northern | 6 | 36 | 40 | 60 | 54 | 12 | 7 | 4 | 14 | 7 | | 53 | 24 | 1 | 6 | 3 | 321 |
| Mabuiag | 7 | 502 | 1107 | 430 | 482 | 272 | 102 | 15 | 409 | 141 | | 799 | 252 | 24 | 9 | 85 | 4629 |
| Badu | 8 | 342 | 1063 | 583 | 703 | 429 | 26 | 49 | 356 | 174 | | 246 | 370 | 218 | 191 | 218 | 4968 |
| Thurs Is | 9 | 1384 | 1583 | 761 | 2025 | 2254 | 2373 | 2180 | 722 | 535 | | 58 | 703 | 853 | 2066 | 917 | 18414 |
| Central | 10 | 39 | 131 | 85 | 134 | 39 | 16 | 8 | 26 | 27 | | 26 | 11 | 1 | 67 | 15 | 625 |
| Warrior | 11 | 15 | 751 | 341 | 459 | 335 | 193 | 17 | 5 | 0 | | 0 | 22 | 46 | 12 | 231 | 2427 |
| Warraber | 12 | 192 | 200 | 372 | 595 | 452 | 244 | 154 | 92 | 49 | | 260 | 302 | 253 | 28 | 137 | 3330 |
| Adolphus | 13 | 95 | 72 | 112 | 112 | 52 | 9 | 43 | 51 | 4 | | 7 | 6 | 3 | 3 | 13 | 582 |
| Great NE | 14 | 135 | 138 | 188 | 126 | 186 | 212 | 106 | 86 | 21 | | 15 | 10 | 89 | 47 | 235 | 1594 |
| GBR | 15 | 10 | 40 | 29 | 98 | 35 | 29 | 3 | 1 | 0 | | 0 | 2 | 1 | 0 | 1 | 249 |
| Darnley | 16 | 77 | 245 | 127 | 263 | 121 | 0 | 45 | 30 | 10 | | 0 | 3 | 3 | 11 | 39 | 974 |
| Cumber | 17 | 23 | 116 | 162 | 259 | 128 | 0 | 1 | 0 | 0 | | 1 | 0 | 0 | 2 | 32 | 724 |
| Total | | 2850 | 5486 | 3250 | 5310 | 4315 | 3211 | 2625 | 1792 | 968 | 0 | 1465 | 1705 | 1492 | 2442 | 1926 | 38837 |

(b) Total Number of DAYS_FISHED

| AREA | AREA | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Northern | 6 | 74 | 53 | 77 | 87 | 27 | 10 | 6 | 16 | 9 | | 91 | 51 | 1 | 12 | 5 | 519 |
| Mabuiag | 7 | 552 | 1735 | 700 | 666 | 318 | 334 | 41 | 552 | 387 | | 972 | 316 | 27 | 29 | 216 | 6845 |
| Badu | 8 | 378 | 1103 | 615 | 749 | 471 | 31 | 65 | 565 | 464 | | 707 | 1011 | 648 | 288 | 313 | 7408 |
| Thurs Is | 9 | 1545 | 1719 | 802 | 2311 | 2364 | 2452 | 2296 | 730 | 554 | | 59 | 711 | 859 | 2093 | 1086 | 19581 |
| Central | 10 | 76 | 159 | 115 | 141 | 57 | 16 | 10 | 31 | 34 | | 53 | 33 | 2 | 89 | 21 | 837 |
| Warrior | 11 | 36 | 758 | 394 | 560 | 424 | 263 | 22 | 7 | 0 | | 0 | 66 | 51 | 35 | 435 | 3051 |
| Warraber | 12 | 507 | 456 | 728 | 822 | 783 | 472 | 308 | 103 | 51 | | 520 | 583 | 471 | 35 | 199 | 6038 |
| Adolphus | 13 | 183 | 143 | 161 | 155 | 92 | 13 | 99 | 58 | 6 | | 7 | 7 | 3 | 5 | 16 | 948 |
| Great NE | 14 | 349 | 288 | 246 | 170 | 252 | 629 | 205 | 95 | 28 | | 18 | 16 | 200 | 80 | 392 | 2968 |
| GBR | 15 | 23 | 73 | 46 | 139 | 69 | 33 | 5 | 1 | 0 | | 0 | 5 | 1 | 0 | 4 | 399 |
| Darnley | 16 | 93 | 293 | 141 | 266 | 123 | 0 | 49 | 30 | 15 | | 0 | 3 | 3 | 12 | 47 | 1075 |
| Cumber | 17 | 37 | 180 | 229 | 352 | 207 | 0 | 1 | 0 | 0 | | 1 | 0 | 0 | 2 | 79 | 1088 |
| Total | | 3853 | 6960 | 4254 | 6418 | 5187 | 4253 | 3107 | 2188 | 1548 | 0 | 2428 | 2802 | 2266 | 2680 | 2813 | 50757 |

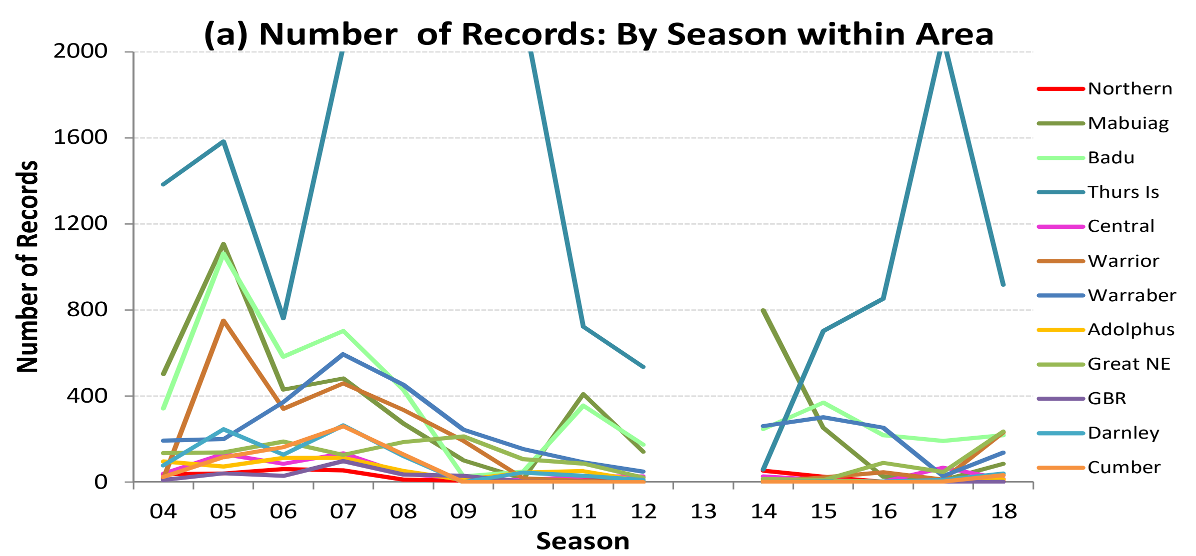
(c) Total CATCH_WEIGHT

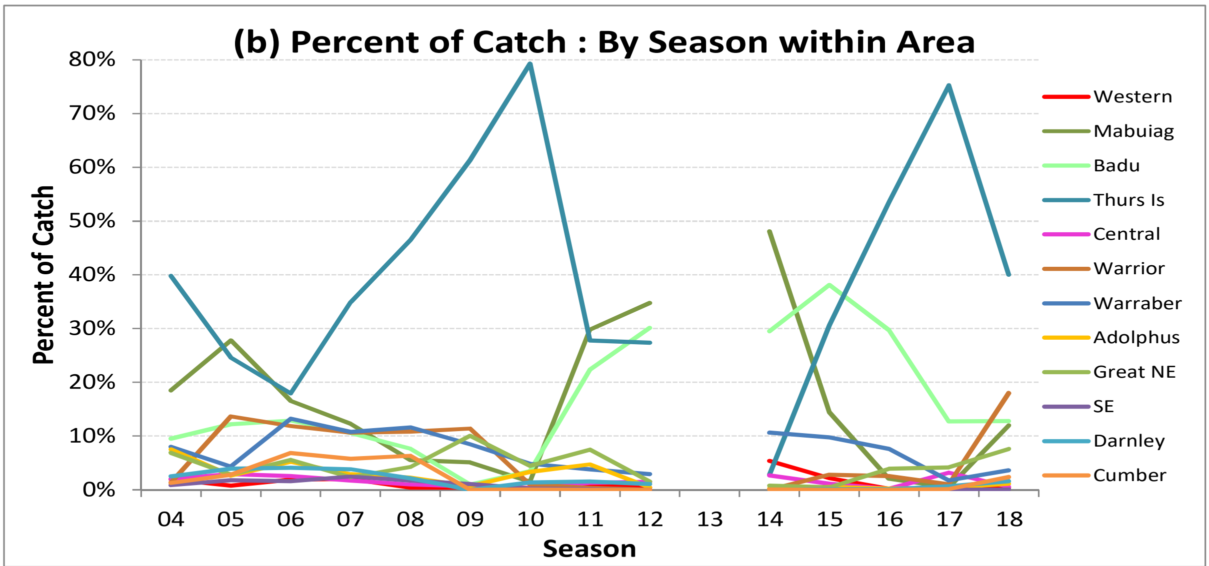
| AREA | AREA | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Northern | 6 | 2303 | 1982 | 2043 | 3920 | 553 | 503 | 333 | 915 | 237 | | 3941 | 1353 | 99 | 323 | 247 | 18752 |
| Mabuiag | 7 | 21999 | 71500 | 17896 | 24174 | 8498 | 6001 | 1371 | 30682 | 20259 | | 35484 | 9102 | 1385 | 306 | 9215 | 257872 |
| Badu | 8 | 11334 | 31390 | 13922 | 20703 | 11831 | 1138 | 3224 | 23002 | 17574 | | 21767 | 24121 | 20364 | 8840 | 9839 | 219050 |
| Thurs Is | 9 | 47450 | 63302 | 19376 | 68655 | 71844 | 72268 | 74548 | 28615 | 15954 | | 2076 | 19339 | 36708 | 52464 | 30858 | 603456 |
| Central | 10 | 2370 | 7465 | 2733 | 3415 | 1465 | 735 | 282 | 1336 | 847 | | 1976 | 696 | 98 | 2201 | 409 | 26027 |
| Warrior | 11 | 1548 | 35041 | 12813 | 20843 | 16736 | 13395 | 916 | 352 | 0 | | 0 | 1769 | 1739 | 708 | 13884 | 119745 |
| Warraber | 12 | 9483 | 11071 | 14282 | 21084 | 17940 | 9924 | 4531 | 3892 | 1698 | | 7833 | 6163 | 5214 | 1191 | 2773 | 117077 |
| Adolphus | 13 | 8934 | 6690 | 5609 | 5624 | 3465 | 777 | 3118 | 4867 | 238 | | 187 | 333 | 126 | 248 | 880 | 41096 |
| Great NE | 14 | 8208 | 7153 | 6008 | 4574 | 6577 | 11798 | 4175 | 7680 | 885 | | 558 | 275 | 2675 | 2904 | 5848 | 69319 |
| GBR | 15 | 990 | 4502 | 1717 | 4814 | 2577 | 1256 | 196 | 135 | 0 | | 0 | 27 | 54 | 0 | 50 | 16317 |
| Darnley | 16 | 2985 | 10061 | 4391 | 7506 | 3273 | 0 | 1271 | 1552 | 601 | | 0 | 72 | 89 | 436 | 1221 | 33457 |
| Cumber | 17 | 1525 | 7140 | 7406 | 11364 | 9747 | 0 | 31 | 0 | 0 | | 20 | 0 | 0 | 77 | 1833 | 39143 |
| Total | | 119129 | 257297 | 108196 | 196676 | 154506 | 117795 | 93996 | 103028 | 58293 | 0 | 73842 | 63250 | 68551 | 69698 | 77057 | 1561311 |

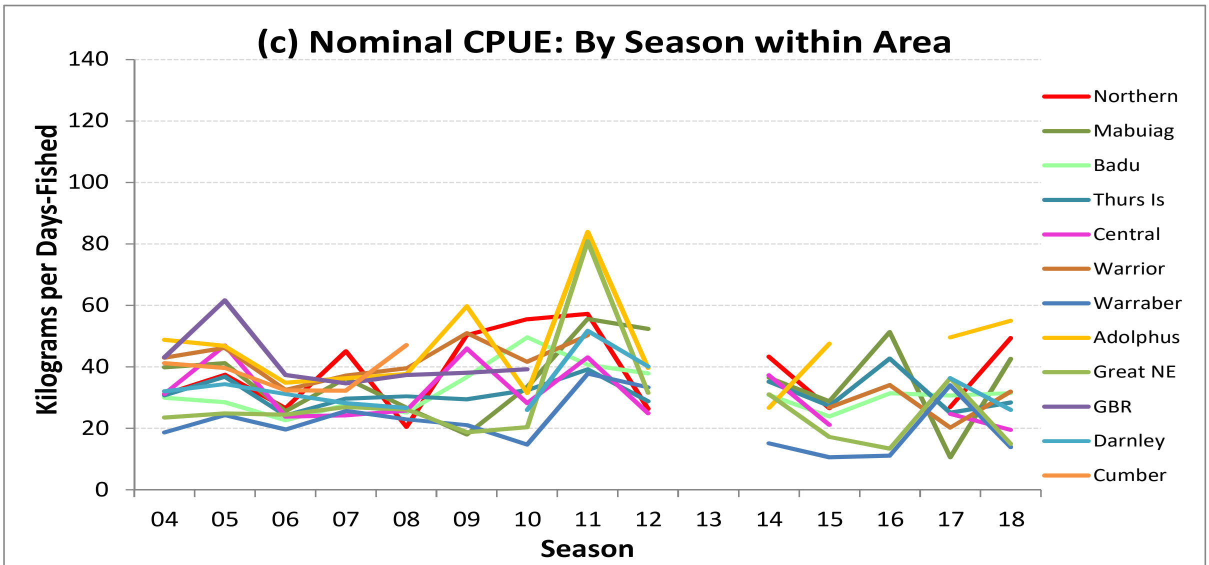
(d) Nominal CPUE

| AREA | AREA | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Northern | 6 | 31.1 | 37.4 | 26.5 | 45.1 | 20.5 | 50.3 | 55.5 | 57.2 | 26.3 | | 43.3 | 26.5 | | 26.9 | 49.4 | 36.1 |
| Mabuiag | 7 | 39.9 | 41.2 | 25.6 | 36.3 | 26.7 | 18.0 | 33.4 | 55.6 | 52.3 | | 36.5 | 28.8 | 51.3 | 10.6 | 42.7 | 37.7 |
| Badu | 8 | 30.0 | 28.5 | 22.6 | 27.6 | 25.1 | 36.7 | 49.6 | 40.7 | 37.9 | | 30.8 | 23.9 | 31.4 | 30.7 | 31.4 | 29.6 |
| Thurs Is | 9 | 30.7 | 36.8 | 24.2 | 29.7 | 30.4 | 29.5 | 32.5 | 39.2 | 28.8 | | 35.2 | 27.2 | 42.7 | 25.1 | 28.4 | 30.8 |
| Central | 10 | 31.2 | 46.9 | 23.8 | 24.2 | 25.7 | 45.9 | 28.2 | 43.1 | 24.9 | | 37.3 | 21.1 | | 24.7 | 19.5 | 31.1 |
| Warrior | 11 | 43.0 | 46.2 | 32.5 | 37.2 | 39.5 | 50.9 | 41.6 | 50.3 | | | | 26.8 | 34.1 | 20.2 | 31.9 | 39.2 |
| Warraber | 12 | 18.7 | 24.3 | 19.6 | 25.6 | 22.9 | 21.0 | 14.7 | 37.8 | 33.3 | | 15.1 | 10.6 | 11.1 | 34.0 | 13.9 | 19.4 |
| Adolphus | 13 | 48.8 | 46.8 | 34.8 | 36.3 | 37.7 | 59.8 | 31.5 | 83.9 | 39.7 | | 26.7 | 47.6 | | 49.6 | 55.0 | 43.4 |
| Great NE | 14 | 23.5 | 24.8 | 24.4 | 26.9 | 26.1 | 18.8 | 20.4 | 80.8 | 31.6 | | 31.0 | 17.2 | 13.4 | 36.3 | 14.9 | 23.4 |
| GBR | 15 | 43.0 | 61.7 | 37.3 | 34.6 | 37.3 | 38.1 | 39.2 | | | | | 5.4 | | | | 40.9 |
| Darnley | 16 | 32.1 | 34.3 | 31.1 | 28.2 | 26.6 | | 25.9 | 51.7 | 40.1 | | | | | 36.3 | 26.0 | 31.1 |
| Cumber | 17 | 41.2 | 39.7 | 32.3 | 32.3 | 47.1 | | | | | | | | | | 23.2 | 36.0 |
| Total | | 30.9 | 37.0 | 25.4 | 30.6 | 29.8 | 27.7 | 30.3 | 47.1 | 37.7 | | 30.4 | 22.6 | 30.3 | 26.0 | 27.4 | 30.8 |

Appendix B (i). Number of GLM data records, percent of catch, and associated CPUE in each Season*Area strata. Note, nominal CPUE is only shown for strata where the number of the days fished is 5 or greater.



Appendix B (ii). Number of GLM data records, total number of days fished, total catch weight, and associated CPUE in each Season*Month strata. Note, strata with less than 10 records are shaded (dark shading where number is zero) and nominal CPUE is only shown for strata where the number of the days fished is 5 or greater.

(a) Number of TIB RECORDS

| | | Season | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | Month | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | Total |
| Dec | 12 | 0 | 447 | 274 | 401 | 282 | 229 | 217 | 146 | 196 | | 74 | 271 | 76 | 51 | 243 | 2907 |
| Jan | 1 | 289 | 321 | 250 | 576 | 351 | 331 | 204 | 237 | 230 | | 128 | 130 | 70 | 184 | 212 | 3513 |
| Feb | 2 | 339 | 574 | 595 | 571 | 657 | 417 | 450 | 408 | 117 | | 152 | 286 | 260 | 371 | 339 | 5536 |
| Mar | 3 | 447 | 659 | 658 | 1040 | 919 | 547 | 410 | 291 | 140 | | 172 | 192 | 192 | 376 | 272 | 6315 |
| Apr | 4 | 227 | 649 | 443 | 564 | 611 | 409 | 330 | 114 | 65 | | 153 | 192 | 152 | 263 | 285 | 4457 |
| May | 5 | 356 | 755 | 437 | 675 | 357 | 315 | 234 | 154 | 53 | | 126 | 153 | 147 | 293 | 179 | 4234 |
| Jun | 6 | 347 | 726 | 214 | 509 | 325 | 310 | 266 | 156 | 75 | | 139 | 158 | 147 | 244 | 168 | 3784 |
| Jul | 7 | 397 | 587 | 224 | 401 | 443 | 299 | 189 | 163 | 39 | | 153 | 127 | 184 | 254 | 228 | 3688 |
| Aug | 8 | 283 | 414 | 96 | 312 | 208 | 201 | 219 | 81 | 35 | | 204 | 109 | 167 | 260 | 0 | 2589 |
| Sep | 9 | 165 | 354 | 59 | 261 | 162 | 153 | 106 | 42 | 18 | | 164 | 87 | 97 | 146 | 0 | 1814 |
| Total | | 2850 | 5486 | 3250 | 5310 | 4315 | 3211 | 2625 | 1792 | 968 | 0 | 1465 | 1705 | 1492 | 2442 | 1926 | 38837 |

(b) Total Number of DAYS_FISHED

| Month | Month | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dec | 12 | | 532 | 342 | 488 | 327 | 265 | 266 | 154 | 212 | | 122 | 390 | 142 | 54 | 390 | 3684 |
| Jan | 1 | 322 | 380 | 323 | 730 | 417 | 426 | 250 | 245 | 284 | | 184 | 183 | 131 | 194 | 352 | 4421 |
| Feb | 2 | 394 | 703 | 685 | 652 | 739 | 550 | 477 | 413 | 238 | | 264 | 451 | 378 | 426 | 406 | 6776 |
| Mar | 3 | 500 | 897 | 821 | 1249 | 1011 | 654 | 441 | 294 | 288 | | 364 | 329 | 374 | 417 | 393 | 8032 |
| Apr | 4 | 300 | 854 | 613 | 647 | 715 | 525 | 376 | 157 | 125 | | 314 | 311 | 237 | 283 | 410 | 5867 |
| May | 5 | 584 | 927 | 608 | 805 | 425 | 365 | 270 | 291 | 118 | | 260 | 278 | 229 | 311 | 281 | 5752 |
| Jun | 6 | 513 | 896 | 346 | 644 | 431 | 433 | 321 | 240 | 144 | | 228 | 289 | 199 | 271 | 268 | 5223 |
| Jul | 7 | 567 | 755 | 270 | 539 | 604 | 451 | 251 | 243 | 84 | | 250 | 238 | 238 | 269 | 313 | 5072 |
| Aug | 8 | 452 | 579 | 158 | 360 | 323 | 362 | 289 | 109 | 37 | | 261 | 185 | 219 | 288 | 0 | 3622 |
| Sep | 9 | 221 | 437 | 88 | 304 | 195 | 222 | 166 | 42 | 18 | | 181 | 148 | 119 | 167 | 0 | 2308 |
| Total | | 3853 | 6960 | 4254 | 6418 | 5187 | 4253 | 3107 | 2188 | 1548 | 0 | 2428 | 2802 | 2266 | 2680 | 2813 | 50757 |

(c) Total CATCH_WEIGHT

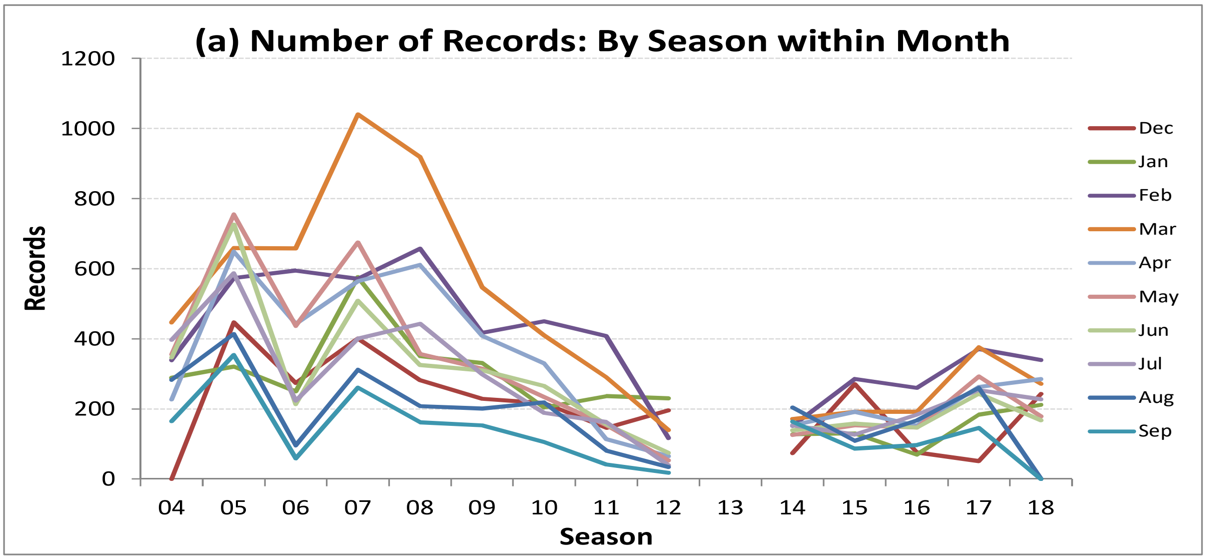
| Month | Month | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dec | 12 | | 14348 | 8792 | 13095 | 9198 | 7607 | 5128 | 5742 | 5634 | | 4438 | 7251 | 2851 | 1198 | 9246 | 94528 |
| Jan | 1 | 9619 | 10498 | 7195 | 18559 | 11385 | 11833 | 4847 | 12306 | 7398 | | 5640 | 3632 | 2906 | 4545 | 6782 | 117146 |
| Feb | 2 | 14636 | 29970 | 18553 | 19205 | 24185 | 16595 | 18247 | 20415 | 9490 | | 8399 | 11035 | 12530 | 11280 | 11024 | 225565 |
| Mar | 3 | 18196 | 35730 | 21822 | 42928 | 30872 | 20555 | 13935 | 17776 | 14318 | | 11665 | 6813 | 11018 | 11174 | 10489 | 267293 |
| Apr | 4 | 9737 | 35605 | 15571 | 22240 | 21233 | 17615 | 12849 | 8175 | 5012 | | 10323 | 9126 | 7333 | 7872 | 11985 | 194677 |
| May | 5 | 17958 | 39627 | 14676 | 24832 | 13835 | 12130 | 9208 | 12881 | 4731 | | 7145 | 5722 | 7881 | 8514 | 7942 | 187081 |
| Jun | 6 | 15533 | 33197 | 8111 | 21095 | 12190 | 10868 | 9962 | 9257 | 5766 | | 6506 | 6631 | 6872 | 6589 | 8182 | 160760 |
| Jul | 7 | 14330 | 27713 | 7026 | 14964 | 19342 | 9980 | 6725 | 10645 | 3399 | | 6693 | 6023 | 7019 | 7845 | 11409 | 153111 |
| Aug | 8 | 12929 | 18362 | 4271 | 11446 | 7152 | 6518 | 8470 | 4095 | 1550 | | 7874 | 4306 | 7329 | 7579 | 0 | 101880 |
| Sep | 9 | 6191 | 12245 | 2179 | 8310 | 5112 | 4092 | 4625 | 1737 | 995 | | 5159 | 2712 | 2811 | 3101 | 0 | 59269 |
| Total | | 119129 | 257295 | 108196 | 196674 | 154504 | 117793 | 93996 | 103029 | 58293 | 0 | 73842 | 63251 | 68550 | 69697 | 77059 | 1561310 |

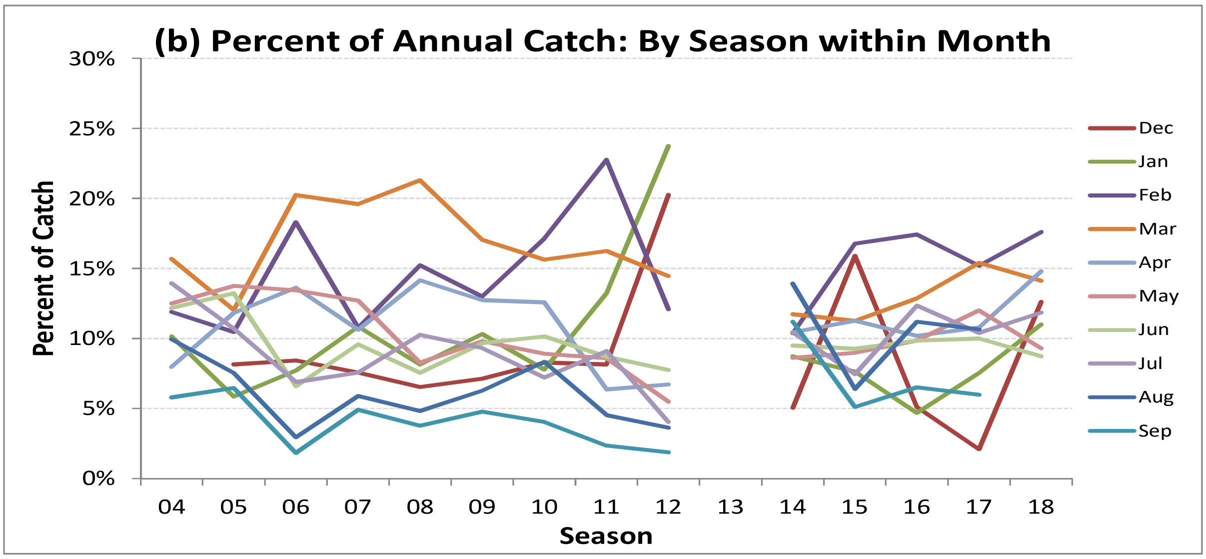
5

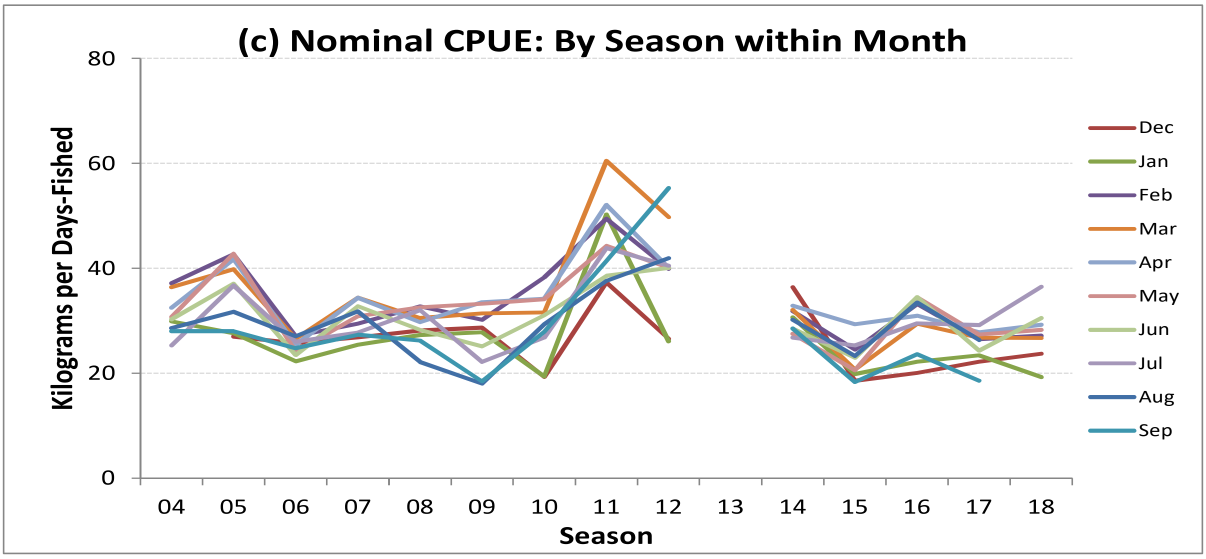
(d) Nominal CPUE (where Days-Fished > 4 days)

| Month | Month | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dec | 12 | | 27.0 | 25.7 | 26.8 | 28.1 | 28.7 | 19.3 | 37.3 | 26.6 | | 36.4 | 18.6 | 20.1 | 22.2 | 23.7 | 25.7 |
| Jan | 1 | 29.9 | 27.6 | 22.3 | 25.4 | 27.3 | 27.8 | 19.4 | 50.2 | 26.0 | | 30.7 | 19.8 | 22.2 | 23.4 | 19.3 | 26.5 |
| Feb | 2 | 37.1 | 42.6 | 27.1 | 29.5 | 32.7 | 30.2 | 38.3 | 49.4 | 39.9 | | 31.8 | 24.5 | 33.1 | 26.5 | 27.2 | 33.3 |
| Mar | 3 | 36.4 | 39.8 | 26.6 | 34.4 | 30.5 | 31.4 | 31.6 | 60.5 | 49.7 | | 32.0 | 20.7 | 29.5 | 26.8 | 26.7 | |
| Apr | 4 | 32.5 | 41.7 | 25.4 | 34.4 | 29.7 | 33.6 | 34.2 | 52.1 | 40.1 | | 32.9 | 29.3 | 30.9 | 27.8 | 29.2 | |
| May | 5 | 30.8 | 42.7 | 24.1 | 30.8 | 32.6 | 33.2 | 34.1 | 44.3 | 40.1 | | 27.5 | 20.6 | 34.4 | 27.4 | 28.3 | |
| Jun | 6 | 30.3 | 37.1 | 23.4 | 32.8 | 28.3 | 25.1 | 31.0 | 38.6 | 40.0 | | 28.5 | 22.9 | 34.5 | 24.3 | 30.5 | |
| Jul | 7 | 25.3 | 36.7 | 26.0 | 27.8 | 32.0 | 22.1 | 26.8 | 43.8 | 40.5 | | 26.8 | 25.3 | 29.5 | 29.2 | 36.5 | |
| Aug | 8 | 28.6 | 31.7 | 27.0 | 31.8 | 22.1 | 18.0 | 29.3 | 37.6 | 41.9 | | 30.2 | 23.3 | 33.5 | 26.3 | | 28.1 |
| Sep | 9 | 28.0 | 28.0 | 24.8 | 27.3 | 26.2 | 18.4 | 27.9 | 41.4 | 55.3 | | 28.5 | 18.3 | 23.6 | 18.6 | | 25.7 |
| Total | | 30.9 | 37.0 | 25.4 | 30.6 | 29.8 | 27.7 | 30.3 | 47.1 | 37.7 | | 30.4 | 22.6 | 30.3 | 26.0 | 27.4 | 30.8 |

Appendix B (ii). Number of GLM data records, percent of catch, and associated nominal CPUE in each Season*Month strata. Note, nominal CPUE is only shown for strata where the number of the days fished is 5 or greater.



Appendix B (iii). Number of GLM data records, total number of days fished, total catch weight, and associated CPUE in each Area*Month strata. Note, strata with less than 10 records are shaded (dark shading where number is zero) and nominal CPUE is only shown for strata where the number of the days fished is 5 or greater.

(a) Number of TIB RECORDS

| | AREA | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Northern | 6 | 17 | 35 | 47 | 45 | 56 | 26 | 27 | 40 | 18 | 10 | 321 |
| Mabuiag | 7 | 365 | 482 | 725 | 840 | 431 | 368 | 415 | 415 | 285 | 303 | 4629 |
| Badu | 8 | 303 | 410 | 874 | 930 | 618 | 567 | 454 | 430 | 224 | 158 | 4968 |
| Thurs Is | 9 | 1202 | 1575 | 2738 | 2972 | 2135 | 2074 | 1785 | 1763 | 1276 | 894 | 18414 |
| Central | 10 | 79 | 89 | 99 | 121 | 59 | 51 | 34 | 34 | 34 | 25 | 625 |
| Warrior | 11 | 363 | 250 | 327 | 352 | 299 | 224 | 197 | 189 | 146 | 80 | 2427 |
| Warraber | 12 | 295 | 302 | 325 | 495 | 394 | 397 | 375 | 380 | 281 | 86 | 3330 |
| Adolphus | 13 | 33 | 46 | 86 | 54 | 69 | 75 | 78 | 61 | 54 | 26 | 582 |
| Great NE | 14 | 87 | 116 | 124 | 216 | 173 | 224 | 219 | 199 | 143 | 93 | 1594 |
| GBR | 15 | 12 | 29 | 32 | 34 | 26 | 20 | 40 | 27 | 12 | 17 | 249 |
| Darnley | 16 | 112 | 119 | 115 | 132 | 107 | 112 | 72 | 53 | 70 | 82 | 974 |
| Cumber | 17 | 39 | 60 | 44 | 124 | 90 | 96 | 88 | 97 | 46 | 40 | 724 |
| | Total | 2907 | 3513 | 5536 | 6315 | 4457 | 4234 | 3784 | 3688 | 2589 | 1814 | 38837 |

(b) Total Number of DAYS_FISHED

| | AREA | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Northern | 6 | 29 | 63 | 76 | 85 | 79 | 33 | 41 | 71 | 29 | 13 | 519 |
| Mabuiag | 7 | 429 | 609 | 1049 | 1218 | 734 | 627 | 655 | 653 | 449 | 422 | 6845 |
| Badu | 8 | 447 | 562 | 1173 | 1379 | 941 | 944 | 717 | 666 | 340 | 239 | 7408 |
| Thurs Is | 9 | 1339 | 1776 | 2836 | 3105 | 2230 | 2223 | 1903 | 1883 | 1361 | 925 | 19581 |
| Central | 10 | 99 | 111 | 106 | 170 | 83 | 61 | 53 | 76 | 51 | 27 | 837 |
| Warrior | 11 | 498 | 309 | 414 | 420 | 351 | 287 | 269 | 233 | 176 | 94 | 3051 |
| Warraber | 12 | 434 | 496 | 558 | 848 | 755 | 758 | 724 | 769 | 556 | 140 | 6038 |
| Adolphus | 13 | 56 | 54 | 116 | 71 | 113 | 132 | 132 | 83 | 130 | 61 | 948 |
| Great NE | 14 | 153 | 196 | 212 | 366 | 295 | 402 | 440 | 352 | 354 | 198 | 2968 |
| GBR | 15 | 19 | 44 | 45 | 50 | 32 | 35 | 60 | 59 | 20 | 35 | 399 |
| Darnley | 16 | 131 | 132 | 121 | 145 | 117 | 124 | 75 | 61 | 79 | 90 | 1075 |
| Cumber | 17 | 50 | 69 | 70 | 175 | 137 | 126 | 154 | 166 | 77 | 64 | 1088 |
| | Total | 3684 | 4421 | 6776 | 8032 | 5867 | 5752 | 5223 | 5072 | 3622 | 2308 | 50757 |

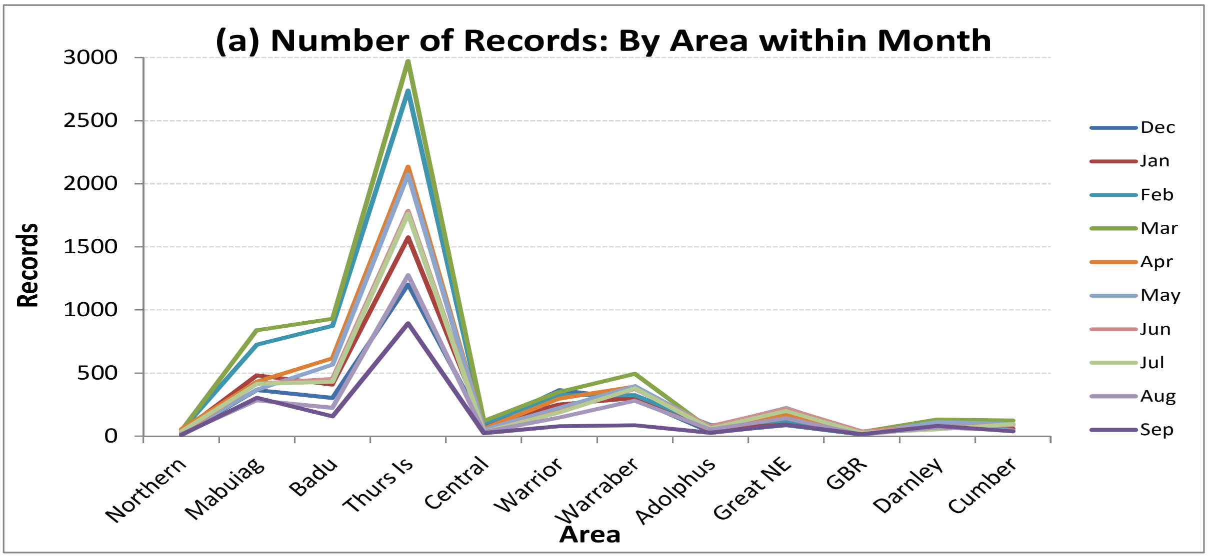
(c) Total CATCH_WEIGHT

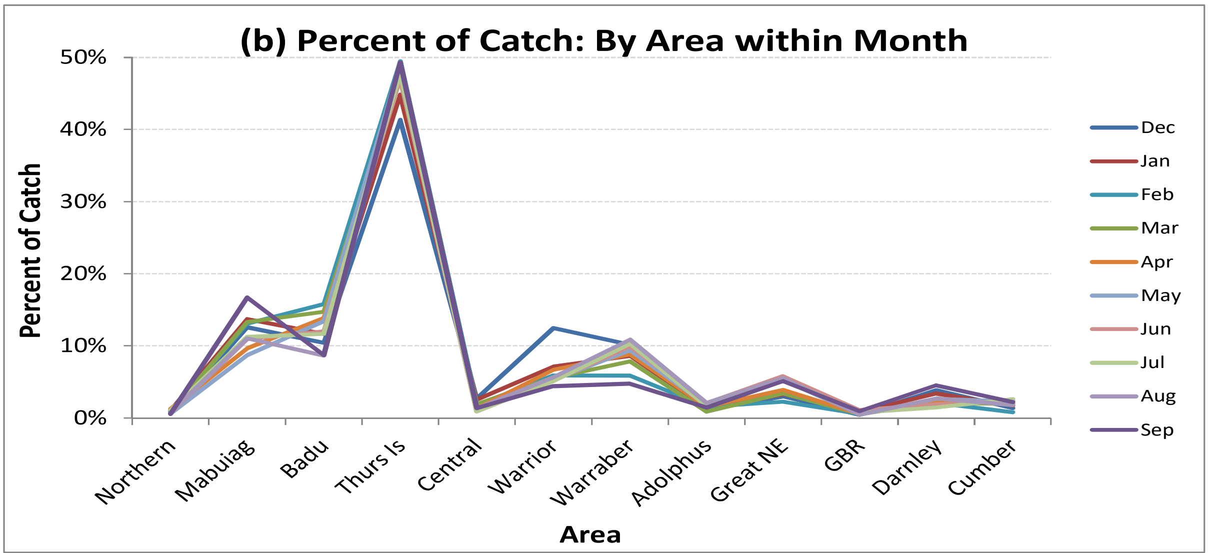
| | AREA | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Northern | 6 | 954 | 2190 | 3382 | 2833 | 3462 | 1581 | 1364 | 1634 | 832 | 519 | 18752 |
| Mabuiag | 7 | 13635 | 23181 | 45964 | 52315 | 27820 | 24793 | 23528 | 21418 | 14431 | 10787 | 257872 |
| Badu | 8 | 11613 | 16323 | 36543 | 43815 | 29128 | 27750 | 20123 | 17763 | 10234 | 5758 | 219050 |
| Thurs Is | 9 | 29604 | 40133 | 95983 | 105041 | 76683 | 72506 | 61557 | 57910 | 39654 | 24385 | 603456 |
| Central | 10 | 2699 | 2868 | 3152 | 5186 | 3004 | 2194 | 2203 | 2014 | 1656 | 1050 | 26027 |
| Warrior | 11 | 16942 | 10903 | 14665 | 14348 | 15365 | 13772 | 12100 | 11586 | 7044 | 3020 | 119745 |
| Warraber | 12 | 7932 | 9690 | 10802 | 17736 | 13929 | 15218 | 14019 | 15269 | 10327 | 2157 | 117077 |
| Adolphus | 13 | 1526 | 1782 | 4074 | 3395 | 6732 | 7334 | 5490 | 4214 | 4545 | 2003 | 41096 |
| Great NE | 14 | 3112 | 3624 | 3855 | 10525 | 7703 | 10811 | 9483 | 9002 | 7289 | 3914 | 69319 |
| GBR | 15 | 540 | 1275 | 1541 | 2622 | 1913 | 1960 | 2346 | 2616 | 677 | 827 | 16317 |
| Darnley | 16 | 4186 | 3505 | 3788 | 4219 | 4335 | 3857 | 2218 | 2093 | 2347 | 2910 | 33457 |
| Cumber | 17 | 1784 | 1672 | 1816 | 5260 | 4602 | 5307 | 6329 | 7591 | 2844 | 1938 | 39143 |
| | Total | 94527 | 117146 | 225565 | 267295 | 194676 | 187083 | 160760 | 153110 | 101880 | 59268 | 1561311 |

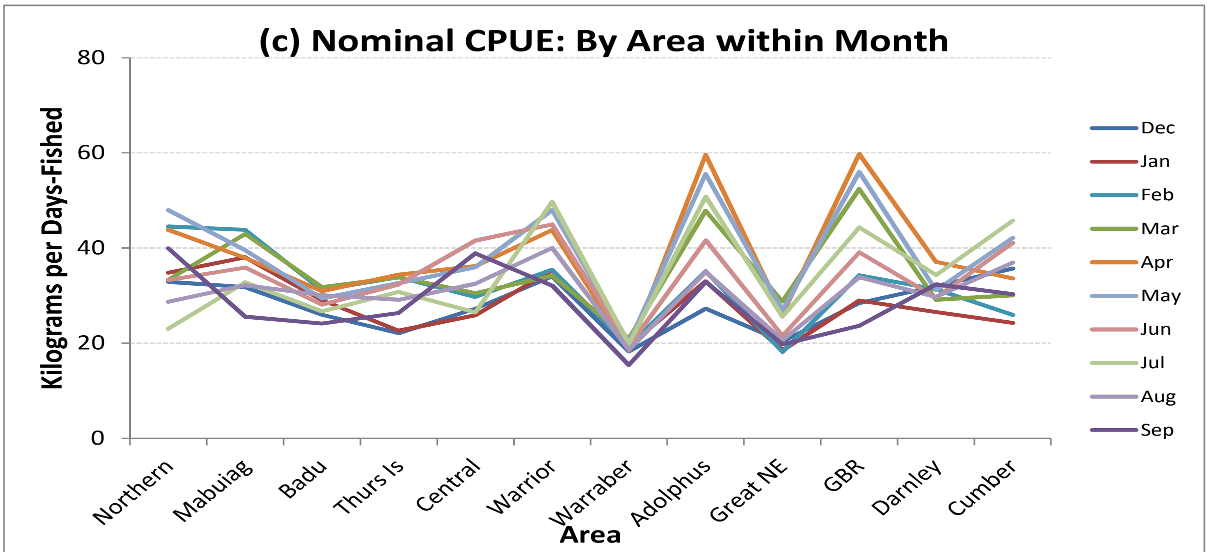
(d) Nominal CPUE

| | AREA | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Northern | 6 | 32.9 | 34.8 | 44.5 | 33.3 | 43.8 | 47.9 | 33.3 | 23.0 | 28.7 | 39.9 | 36.1 |
| Mabuiag | 7 | 31.8 | 38.1 | 43.8 | 43.0 | 37.9 | 39.5 | 35.9 | 32.8 | 32.1 | 25.6 | 37.7 |
| Badu | 8 | 26.0 | 29.0 | 31.2 | 31.8 | 31.0 | 29.4 | 28.1 | 26.7 | 30.1 | 24.1 | 29.6 |
| Thurs Is | 9 | 22.1 | 22.6 | 33.8 | 33.8 | 34.4 | 32.6 | 32.3 | 30.8 | 29.1 | 26.4 | 30.8 |
| Central | 10 | 27.3 | 25.8 | 29.7 | 30.5 | 36.2 | 36.0 | 41.6 | 26.5 | 32.5 | 38.9 | 31.1 |
| Warrior | 11 | 34.0 | 35.3 | 35.4 | 34.2 | 43.8 | 48.0 | 45.0 | 49.7 | 40.0 | 32.1 | 39.2 |
| Warraber | 12 | 18.3 | 19.5 | 19.4 | 20.9 | 18.4 | 20.1 | 19.4 | 19.9 | 18.6 | 15.4 | 19.4 |
| Adolphus | 13 | 27.3 | 33.0 | 35.1 | 47.8 | 59.6 | 55.6 | 41.6 | 50.8 | 35.0 | 32.8 | 43.4 |
| Great NE | 14 | 20.3 | 18.5 | 18.2 | 28.8 | 26.1 | 26.9 | 21.6 | 25.6 | 20.6 | 19.8 | 23.4 |
| GBR | 15 | 28.4 | 29.0 | 34.2 | 52.4 | 59.8 | 56.0 | 39.1 | 44.3 | 33.9 | 23.6 | 40.9 |
| Darnley | 16 | 32.0 | 26.6 | 31.3 | 29.1 | 37.1 | 31.1 | 29.6 | 34.3 | 29.7 | 32.3 | 31.1 |
| Cumber | 17 | 35.7 | 24.2 | 25.9 | 30.1 | 33.6 | 42.1 | 41.1 | 45.7 | 36.9 | 30.3 | 36.0 |
| | Total | 25.7 | 26.5 | 33.3 | 33.3 | 33.2 | 32.5 | 30.8 | 30.2 | 28.1 | 25.7 | 30.8 |

Appendix B (iii). Number of GLM data records, percent of catch, and associated CPUE in each Area*Month strata. Note, nominal CPUE is only shown for strata where the number of the days fished is 5 or greater.



| | |
|---|---|
| **TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG)** | **MEETING 25**<br>**11-12 December 2018** |
| **STOCK ASSESSMENT UPDATE AND RBC** | **Agenda Item 4**<br>**For Discussion and Advice** |

**RECOMMENDATIONS**

1. That the RAG:
   a. **CONSIDER** the preliminary stock assessment update for the Torres Strait Tropical Rock Lobster Fishery (TRL Fishery) following the November 2018 pre-season survey to be presented by the CSIRO Scientific Member;
   b. **DISCUSS** and **PROVIDE ADVICE** on the preliminary Recommended Biological Catch (RBC) for the 2018/19 fishing season;
   c. **NOTE** that a final updated stock assessment will be presented at the next RAG meeting tentatively scheduled for February 2019. RAG advice on the preliminary RBC will be recorded in the meeting record and taken into account in the final updated stock assessment;
   d. **NOTE** the preliminary RBC for the 2018/19 fishing season under the proposed empirical harvest control rule (eHCR) to be presented by the CSIRO Scientific Member.

**KEY ISSUES**

2. The 2018/19 RBC is to be calculated using the integrated fishery stock assessment model and interim harvest strategy (see details below).
3. A preliminary stock assessment update will be presented by the CSIRO Scientific Member at the RAG meeting. The stock assessment update incorporates catch and effort data for the 2017/18 fishing season, historic catch and effort information and the results of the 2018 mid-year and pre-season surveys.
4. The RAG is being asked to review the preliminary stock assessment update and RBC and where relevant provide advice on the findings and/or need for further analysis.
5. The draft Harvest Strategy, including the empirical harvest control rule (eHCR), have not been agreed by the PZJA. This item is to be discussed further under Agenda Item 5. The preliminary RBC as calculated by applying the eHCR will be presented by the CSIRO Scientific Member but is for noting only and will not be used to determine the RBC for the 2018/19 fishing season.

*Interim TRL Harvest Strategy*

6. The interim Harvest Strategy is as follows:
   a. $B_0$ = varied between 0.65 and 0.80 of unfished biomass
   b. $B_{TARG}$ = 0.65 $B_0$
   c. $B_{THRES}$ is the RAG agreed threshold biomass level below which more stringent rules for calculating the total allowable catch apply. $B_{THRES}$ = 0.48.
   d. $B_{LIM}$ = 0.4 $B_0$
   e. $F_{TARG}$ = 0.15 year-1
   f. $F_{LIM}$ = $F_{TARG}$

**Preliminary summary regarding 2018 assessment of Torres Strait tropical lobster TRL stock**

*Éva Plagányi, Judy Upston, Mark Tonks, Nicole Murphy, Rob Campbell, Kinam Salee, Steven Edgar, Roy Deng, Chris Moeseneder*

*With thanks to Tim Skewes and Darren Dennis for their insights*

CSIRO Oceans and Atmosphere

Summary Report for TRLRAG Dec 2018

## SUMMARY

The Integrated Stock Assessment Model is being updated using results from the 2018 TRL Preseason Survey (conducted between the 11th and 23rd November) as well as the Midyear survey conducted during 28th June - 9th July 2018. The full results will be presented in detail at the TRLRAG meeting 11-12 December, Thursday Island, with a full report tabled at the next TRLRAG meeting. This report summarises some data and considerations that are input to and influence the stock assessment and will therefore be discussed at the forthcoming TRLRAG.

### *Understanding data conflicts*

One aspect to be discussed at the meeting pertains to a conflict between the November 2017 0+ survey index (which was very low relative to historical) and the 2018 1+ index (which was closer to average). Given we are reasonably confident in survey observations of 1+ lobsters (for reasons outlined below) we focus here on the anomalous 0+ observations. The stock assessment model is sensitive to the inclusion or exclusion (or downweighting) of the 2017 0+ index, and hence it is important that the TRLRAG consider the basis for including, further downweighting or excluding the index, and this document briefly outlines some alternative hypotheses (Table 1) to explain the data conflict. Depending on which hypotheses are considered most plausible, this influences decisions whether the index should be retained as is or is not considered adequately representative. It should be noted that another reason why the 0+ index is influential in the stock assessment model (despite having a fairly high associated variance estimate) is because the 2018 Preseason 1+ index also has a relatively high associated variance (see Fig. 1) and hence downweighted by the model (because the model likelihood contribution is weighted by the inverse of the variance of each survey observation). Note also that this would not have had only minor impact during the 2017 assessment as the 0+ index did not directly inform on predicted 2+ (fishable) numbers during 2018.

The key survey 1+ and 0+ standardized indices are shown in Figures 1-2. Sensitivity of the stock assessment model to the alternative indices is being investigated. The model uses as the Reference series the Midyear Only (MYO) series based on the 77 sites (rather than the extra 5 sites being included) because that is the most directly comparable to what was done in 2017. Figure 3 shows a comparison of stock assessment model fit to the Preseason indices when (A) including versus (B) excluding (for illustrative purposes) the 2017 0+ index.

***Investigating if there is evidence of a sampling bias due to diver experience***

Appendix 1 summarises a statistical analysis conducted on past Preseason survey data to objectively evaluate the influence of diver experience and skill (in this instance classifying as Gold Standard dive pairs that included the most experienced diver Darren Dennis, who participated in all surveys from 1989 – 2016, when compared with so-called Other (OT) dive pairs, noting that some members also had in excess of a decade's field experience). The preliminary analysis found slightly higher counts on average by GS team, but no statistically significant difference between counts (Appendix 1), supporting that the CSIRO divers are reliable samplers. Thus there is no evidence for a sampling bias having a substantial effect on the 2017 0+ index. The analysis focused on the 0+ index because the 1+ animals are considered sufficiently large to be easily observable during surveys.

***Midyear survey data***

The 2018 Midyear survey data are also highly informative in terms of resolving model data conflicts (see Figures 4-5). Analyses suggested that the statistical analysis applying a mixture model (Fig 7-8) was the preferred method for splitting the 1+ and 2+ cohorts sampled as this is a repeatable and objective method, particularly important for years when there is not a clear division between size-classes (as in 2018). Applying the method resulted in greater consistency with previous results and hence is used as the default index input to the stock assessment model.

***Fitting to CPUE data***

The Reference Case model was fit to the 'Int-1' TVH standardized CPUE series and 'Seller' standardized TIB CPUE series (Campbell et al. 2018) (Fig. 6), with sensitivity to alternative choices to be investigated. The model converged successfully and did not suggest any huge discrepancy when fitting to the CPUE data from either sector. In both cases the observed standardized CPUE index was relatively larger than the corresponding model-estimated biomass, suggesting that the CPUE indices may have slightly overestimated stock biomass (see Appendix 2). However there was not a great discrepancy (Fig 6) because, as previously, the model assumes a hyperstable relationship between CPUE and stock abundance, and this is accounted for in the model comparison. Sensitivities to this assumption will be presented at the RAG.

***Environmental and Sea Surface Temperature (SST) Data for Torres Strait***

Recent available (SST) measurements for Torres Strait were obtained from automated weather stations located at Thursday Island and Masig (http://data.aims.gov.au/aimsrtds/ ) (Fig 9x). Unfortunately there were no data for Thursday Island during 2017. The 2018 data don't suggts that 2018 was an anomalously hot year when compared to 2016 for example (Fig. 9).

The BOM website ENSO Outlook remains at El Niño ALERT. This means the chance of El Niño forming in the coming months is around 70%; triple the normal likelihood, but doesn't mean that an El Niño will necessarily occur (http://www.bom.gov.au/climate/enso/outlook/)

## References


Campbell R et al. 2018. Use of TVH Logbook Data to construct an Annual Abundance Index for Torres Strait Rock Lobster – 2018 Update (**Attachment 3e**)

Campbell R et al. 2018. Use of TIB Docket-Book Data to construct an Annual Abundance Index for Torres Strait Rock Lobster – 2018 Update (**Attachment 3f**)

Skewes TD, Pitcher CR, Dennis DM (1997) Growth of ornate rock lobsters, Panulirus ornatus, in Torres Strait, Australia. Mar Freshwater Res 48:497-501

Table 1. Consideration of alternative hypotheses to explain the low 2017 0+ survey index compared with the 2018 1+ survey index.

| | **Alternative Hypotheses** | **Does it explain low 0+ in Nov 2017?** | **Does it explain 1+ size distribution in June 2018?** | **Notes and evidence** | **PLAUSIBILITY** |
|---|---|---|---|---|---|
| 1 | The 2017 0+ index was negatively biased due to observational error | No (see Appendix 1) | no | There was some concern that as 2017 was the first year without a "gold standard" (GS) diver participating in the survey with considerable experience detecting the small 0+ age class, this may have biased the index negatively. However a statistical comparison of historical performance between GS and Other teams showed that whereas the GS teams generally found slightly more 0+, there was no significant difference between the results, and evidence of rapid learning. Even if the maximum likely bias is applied to the 0+ index, it does not increase it sufficiently to explain the 2018 1+ abundance. | low |
| 2 | The 2017 0+ index was low because of the timing of settlement | maybe | maybe | As lobsters spawn over a period of a few months, there is also approximately 3 months variability in terms of when they settle. In addition, the anomalous environmental conditions in 2016 (influencing the spawners producing the 2017 0+ cohort) could easily have influenced the timing of spawning and successful transport and settlement of pueruli. If settlement occurred earlier than usual, then this could explain relatively larger 1+ observed during 2018, but it means the 0+ would have been easier to observe during the 2017 survey. On the other hand, if settlement occurred later, then this explains the reduced numbers during the survey, but not the larger sizes of 1+ during 2018 (but it's possible that this was a result of a combination of timing of settlement and change in growth rate as below). | medium |
| 3 | Faster growth due to higher temperatures in 2017-2018 and/or reduced density dependence | no | yes | TRL growth is known to increase with increasing SST (Skewes et al. 1997) and there is evidence to suggest that the 2016 high temperatures had an influence on the stock, but there is less | high |

| | | | | | |
|---|---|---|---|---|---|
| | | | | evidence of high temperatures over December 2017-June 2018 (Fig. 9) potentially influencing growth of the recruiting cohort. Differences in growth due to SST will be more substantial for younger animals as the von Bertalanffy growth curve predicts that growth converges as animals approach maturity. Density dependence is also thought to influence growth rates (Skewes et al. 1997), and the relatively low average density of 2+ lobsters during 2018 means the 1+ lobsters would have had access to more favourable habitat and food supplies and this may also have influenced growth rate. The broad spread in size distribution of this cohort suggests these dynamics may have been spatially patchy (and hence that density dependence may have played a role rather than just temperature) and the relatively large sizes of some individuals lends further support to this hypothesis. | |
| 4 | The 2017 0+ index was low because the distribution of settling recruits changed substantially | yes | yes | The recent anomalous environmental conditions would have had an influence on local Torres Strait currents, as well as sand and habitat distribution and quality which could have influenced the spatial pattern of puerulus settlement. There is some evidence from the 2017 preseason survey 0+ spatial distribution data that the pattern differed to that observed in previous years eg lower than usual density in TI_Bridge stratum. The highest densities of 0+ were in the South-East and Mabuiag strata, so its possible that relatively more settlement may have occurred to the north-west to the extent that the index wasn't as comparable as in previous years. Previous research (Skewes et al. 1997) showed that there are differences in growth rate between the four zones (NW,SW,Central, SE), with lobsters being larger in the NW, and this may have contributed to the larger average size of this 1+ cohort (see Tonks et al. 2018). Commercial catch data from 2018 PNG commercial catches also suggested there was good recruitment up north which lends further support to this hypothesis. | very high |

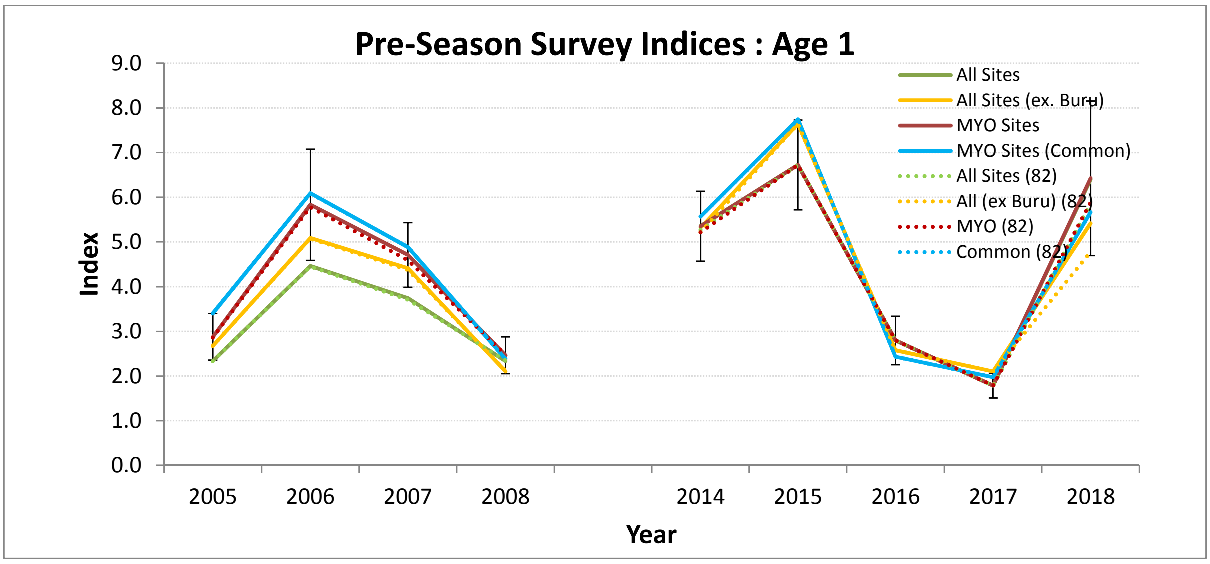



Figure 1. Comparative indices of abundance of recruiting (1+) ornate rock lobsters (*Panulirus ornatus*) recorded during pre-season surveys in Torres Strait between 2005 and 2018 (note surveys were not done during 2009-2013) shown for all sites as well as reduced series including Midyear-Only Sites (MYO). Error bars of MYO indices represent standard errors

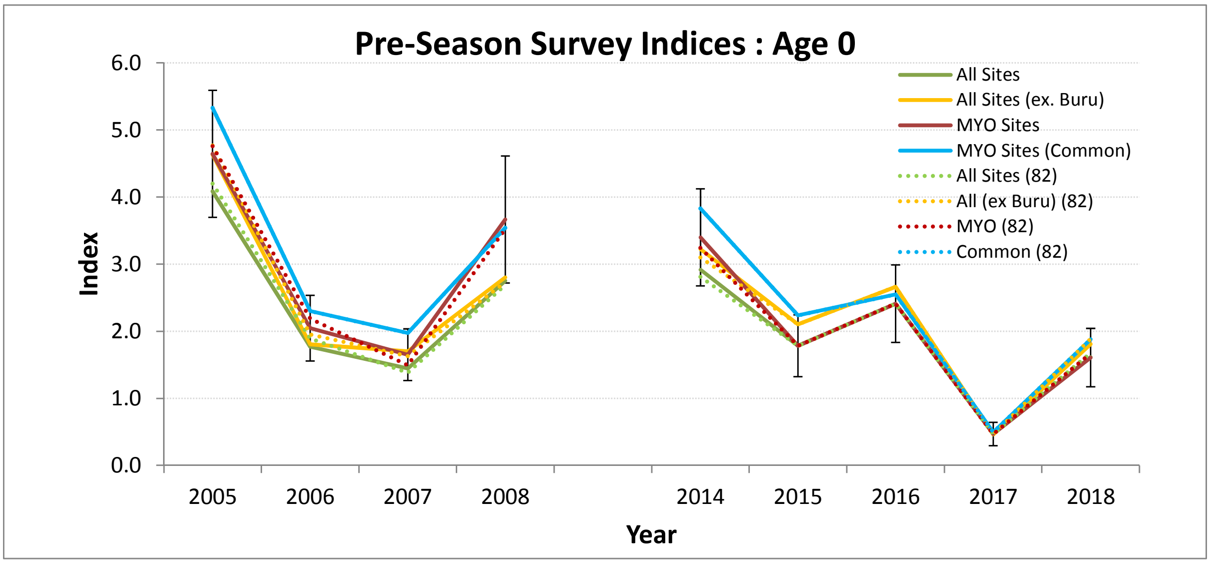



Figure 2. Comparative indices of abundance of newly settled (0+) ornate rock lobsters (*Panulirus ornatus*) recorded during pre-season surveys in Torres Strait between 2005 and 2018 (note surveys were not done during 2009-2013) shown for all sites as well as reduced series including Midyear-Only Sites (MYO). Error bars of MYO indices represent standard errors

# Model vs Observed Preseason Survey Index

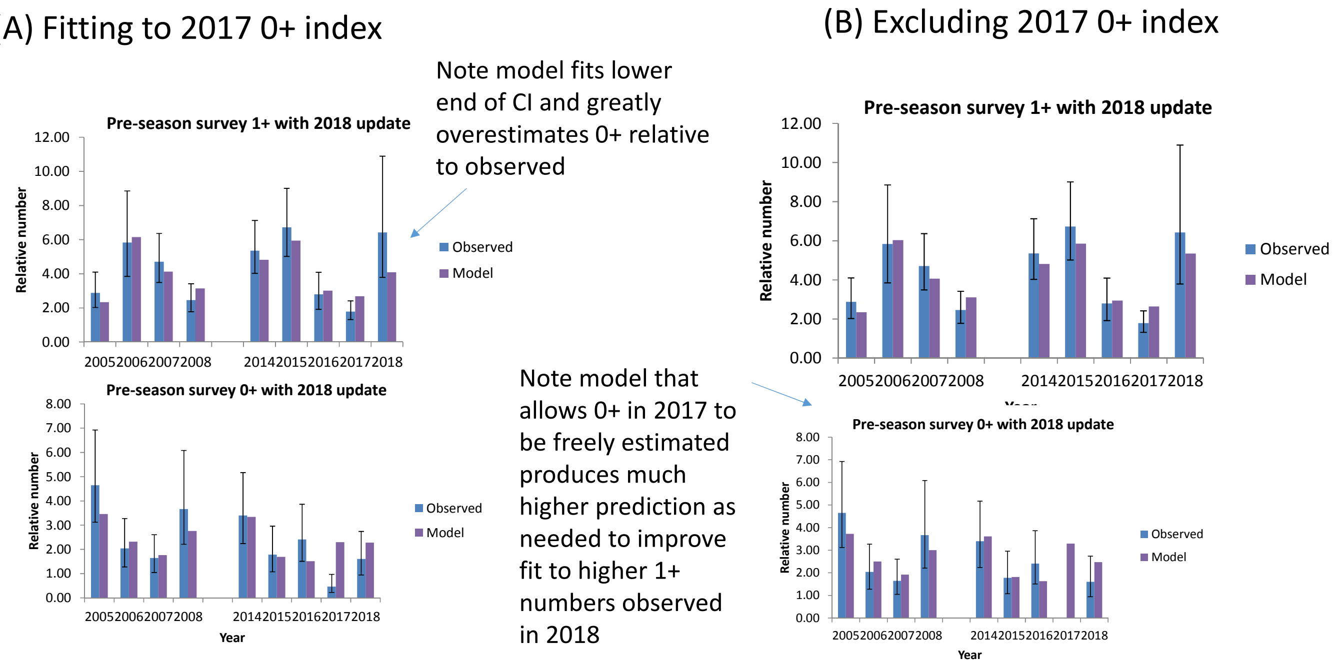



Fig. 3. Comparison of stock assessment model fit to Preseason survey index when (A) including versus (B) excluding (for illustrative purposes) the 2017 0+ index.

# Model vs Observed Midyear survey index of abundance

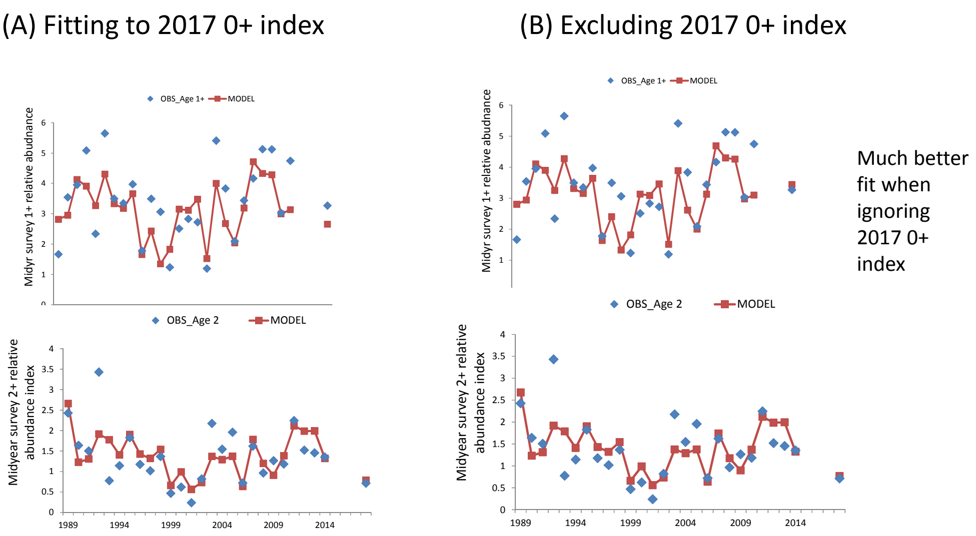



Fig. 4. Comparison of stock assessment model fit to Midyear survey index when (A) including versus (B) excluding (for illustrative purposes) the 2017 0+ index.

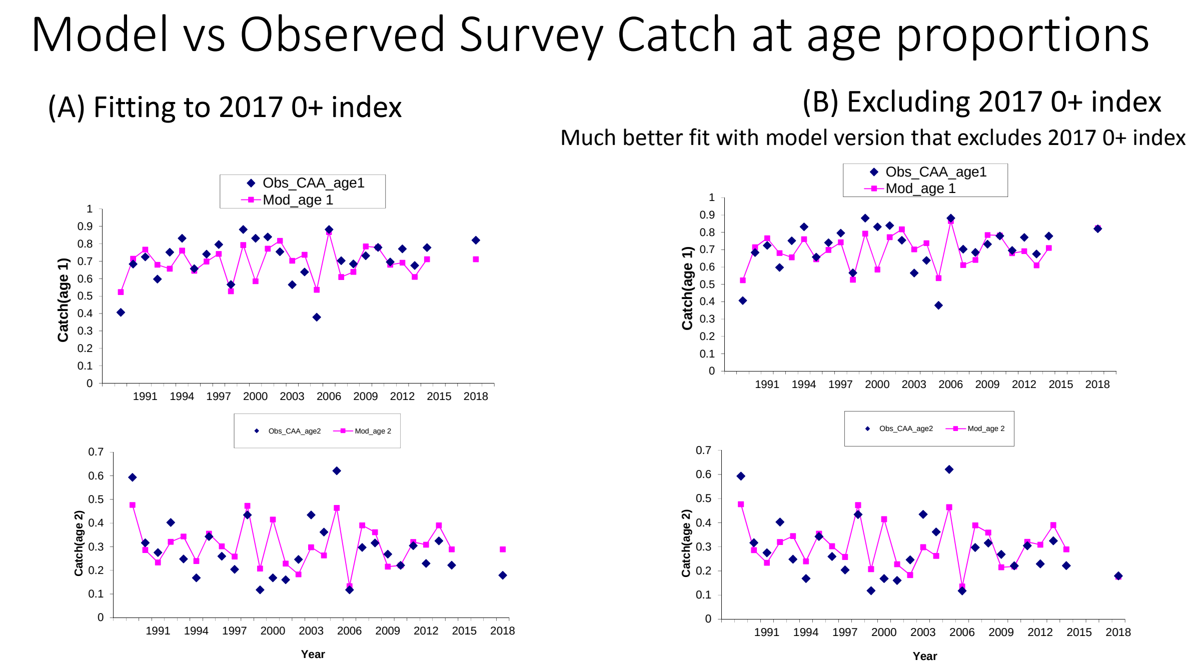



Fig. 5. Comparison of stock assessment model fit to Survey Catch-at-Age information when (A) including versus (B) excluding (for illustrative purposes) the 2017 0+ index.

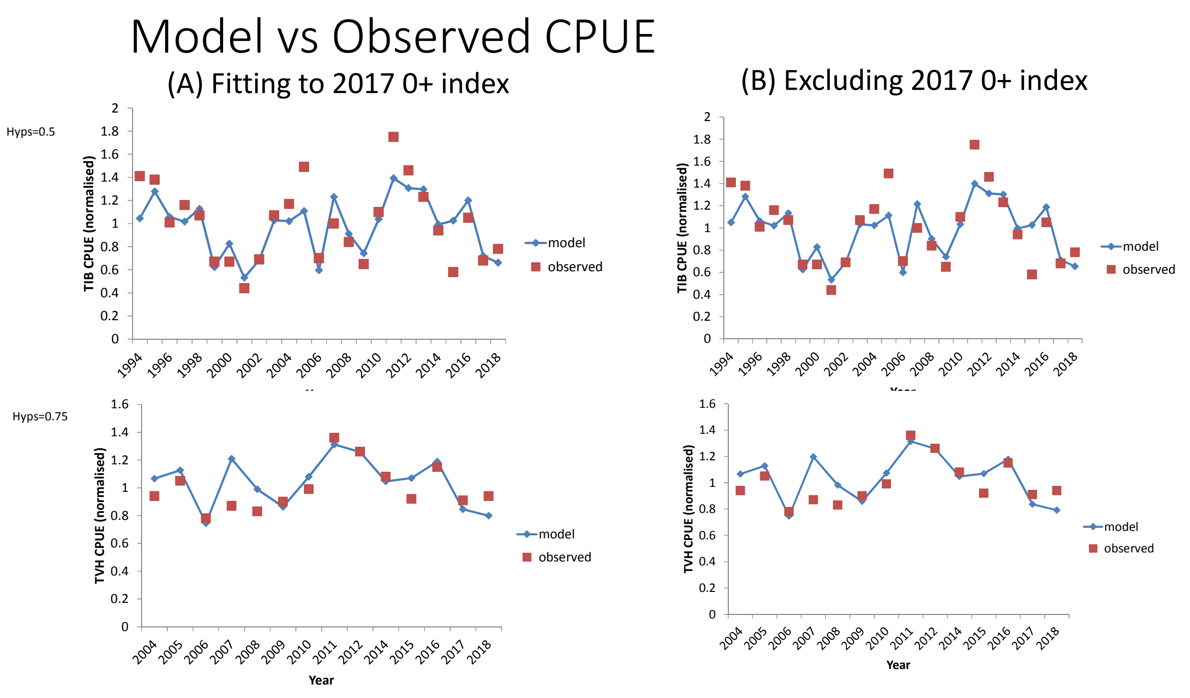



Fig. 6. Comparison of stock assessment model fit to CPUE (TIB top row; TVH bottom row) when (A) including versus (B) excluding (for illustrative purposes) the 2017 0+ index. Results shown use the default hyperstability settings of 0.5 (TIB CPUE) and 0.75 (TVH CPUE) and the Seller and Int-1 standardised series for TIB and TVH respectively.

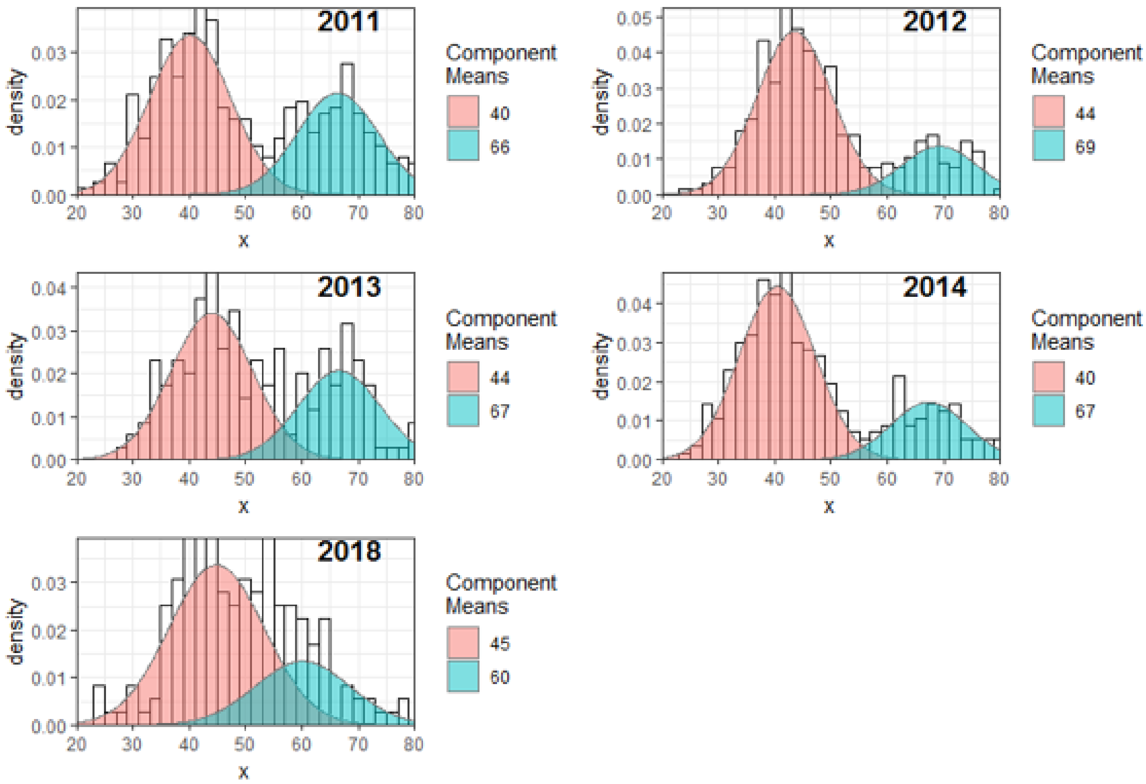



Fig. 7. Mid-year survey mixture distributions and means (recent years), where the horizontal axis shows tail width (mm).

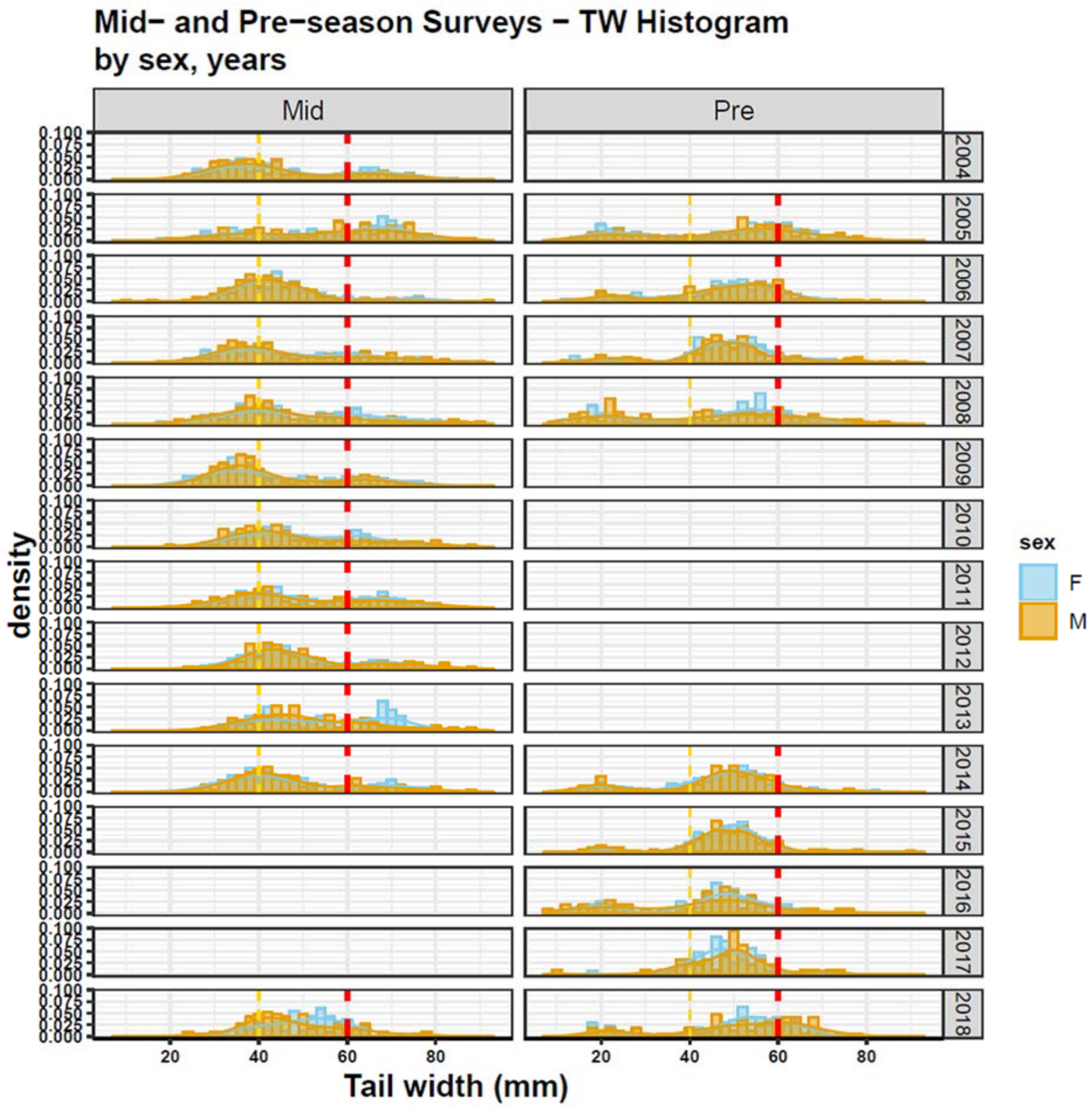



Fig. 8. Comparison of midyear and preseason survey size distributions (tail width (mm) for years as shown.

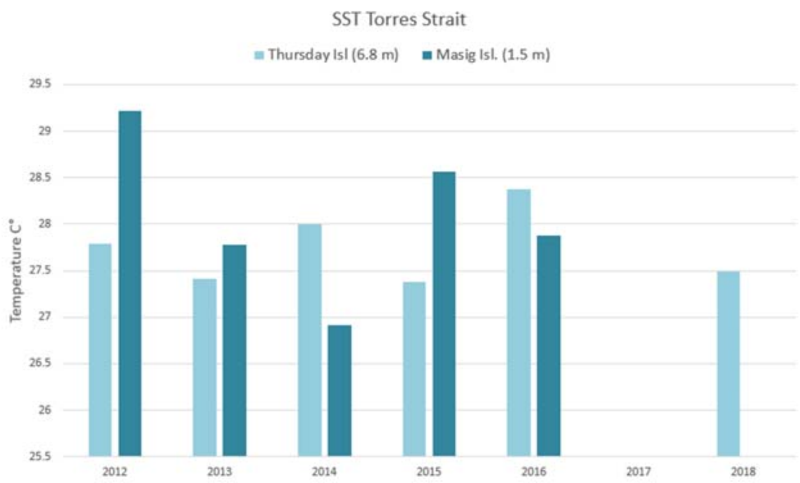



Fig. 9. Yearly average ocean temperatures at Torres Strait, Thursday Island (TS) (6.8 m depth) and Masig Island (MI) (1.5 m depth) for 2012-2018. Averaged from daily values. Data exceptions: TS: from Feb 2012, no data Jan 2013, station offline all of 2017, 2018 to 6 Dec; MI: 2013 only December, 2017 up to 27 Nov. Source AIMS.

**Appendix 1.**

GS = Gold standard (team includes DD) or OT = Other team (without DD).

Zcount refers to 0+ size class (total seen including those speared)

In some earlier years there is a pattern of more 0+ lob seen by GS team, however not significantly different from OT team (usual 95% Cis overlap). Less of a pattern in recent years (2014 on).

Summary all years combined (not including 2017, 2018)

```
summaryz_all
   team  N   Zcount mean_Zcount        se       ci CI_lower CI_upper
1:   GS 18 1.444444    2.874272 0.6774723 1.429342     0.02     2.87
2:   OT 17 1.235294    2.750668 0.6671351 1.414263    -0.18     2.65
```

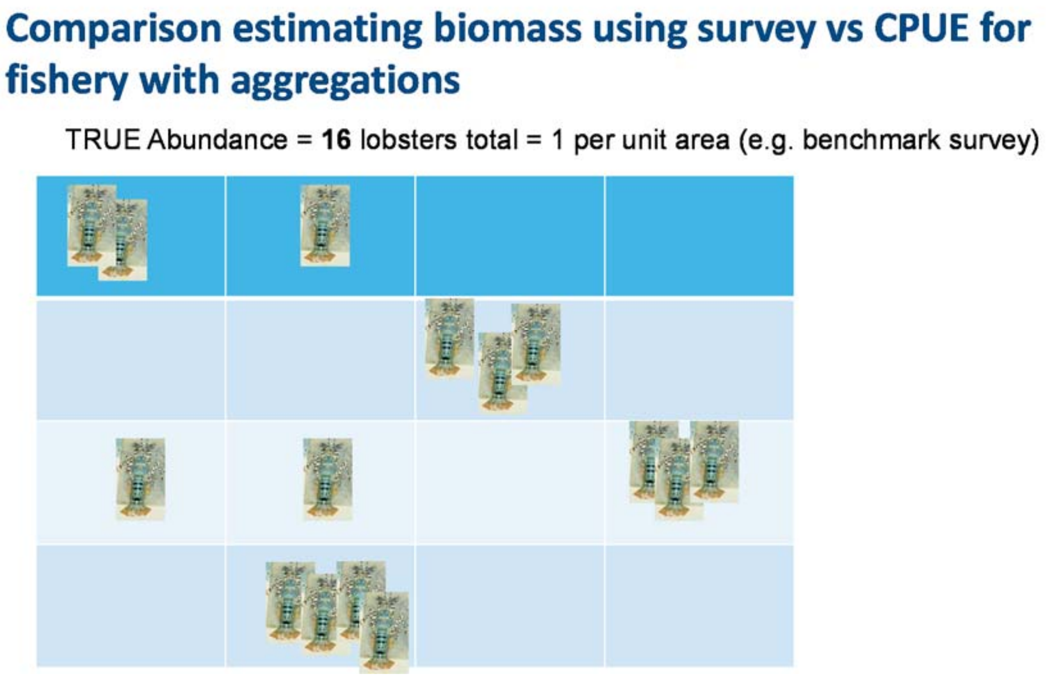
Summary early years (2005 to 2008)

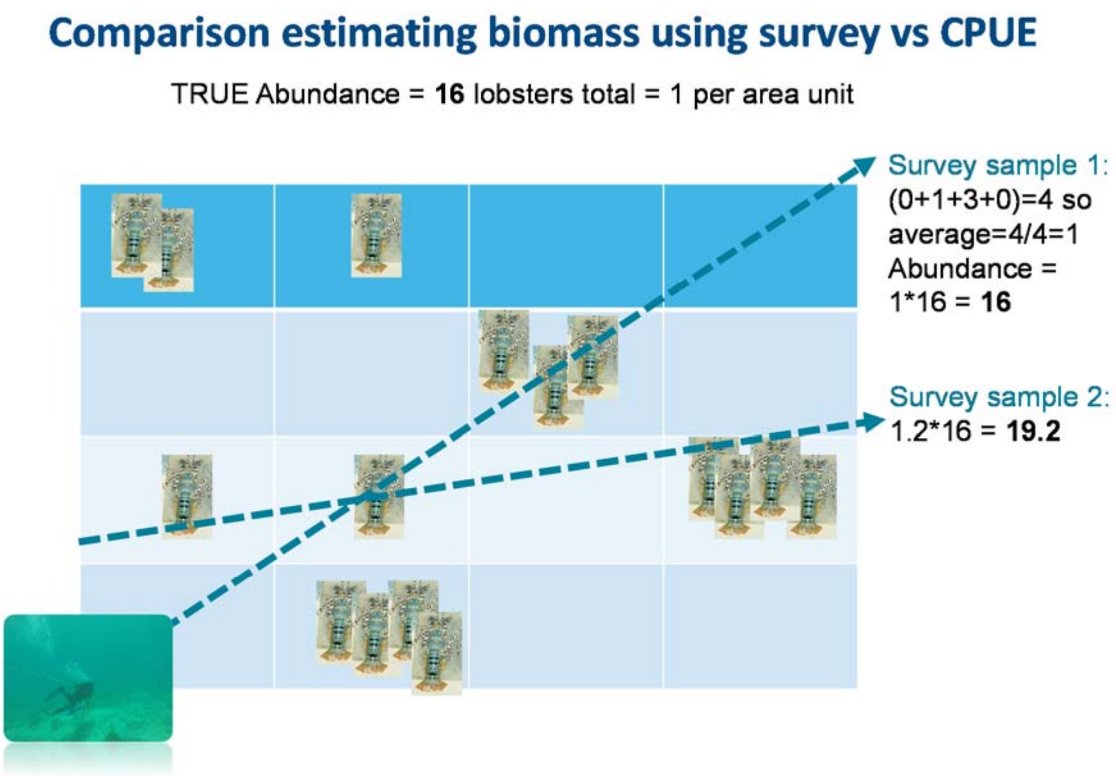
```
summaryz_early
   team   N    Zcount mean_Zcount        se        ci CI_lower CI_upper
1:   GS 218 1.5275229    4.471278 0.3028332 0.5968709     0.93     2.12
2:   OT 461 0.6941432    2.514252 0.1171004 0.2301181     0.46     0.92
```

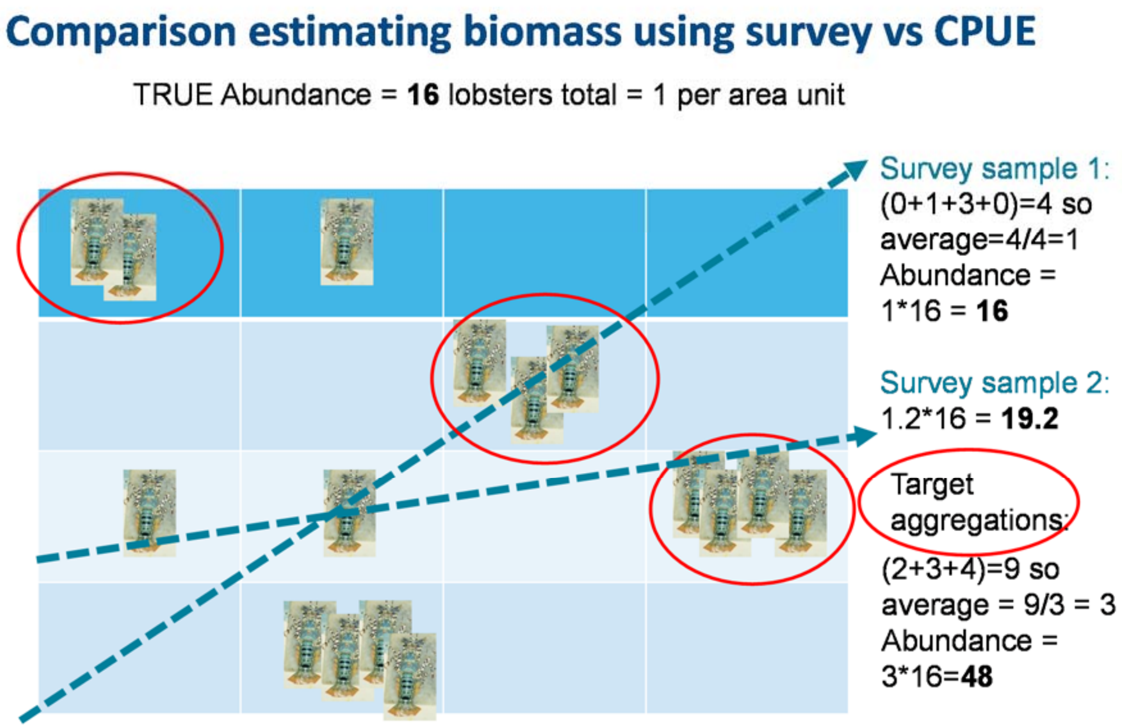
Summary recent years combined (2014, 2015, and 2016)

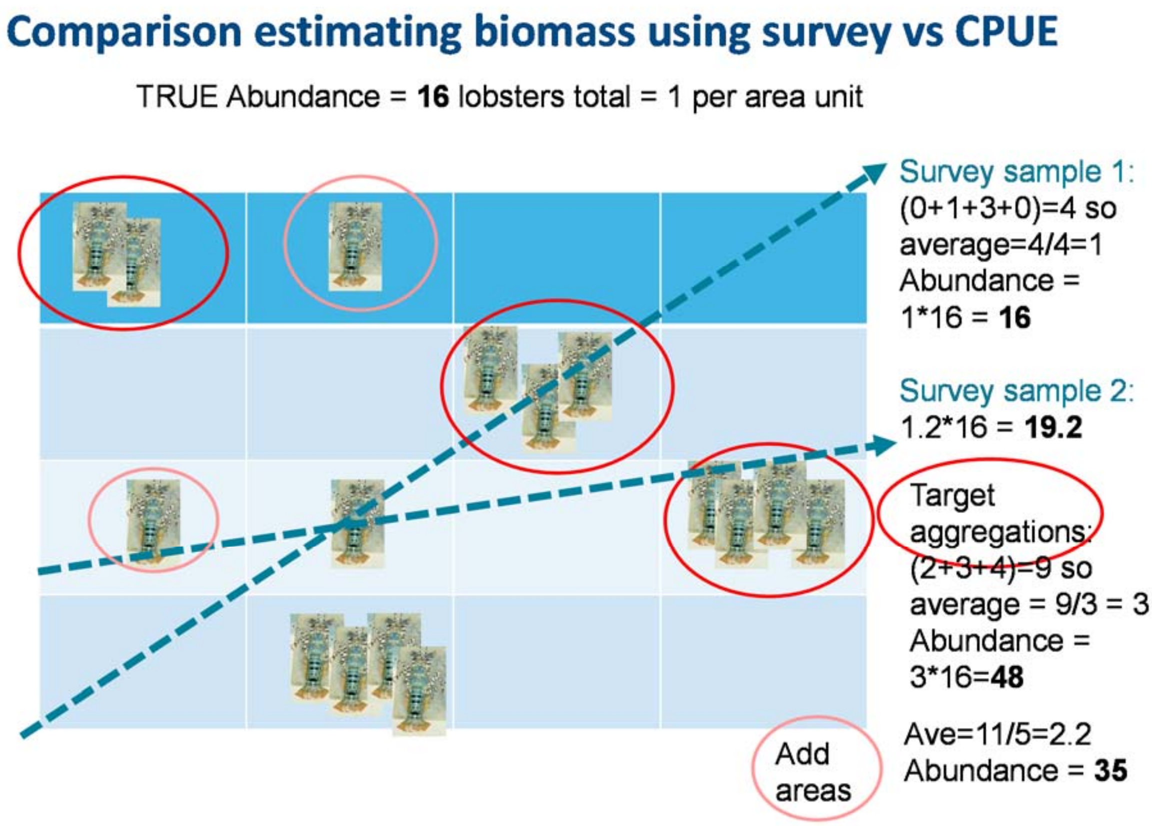
```
summaryz_recent
   team  N   Zcount mean_Zcount        se       ci CI_lower CI_upper
1:   GS 18 1.444444    2.874272 0.6774723 1.429342     0.02     2.87
2:   OT 17 1.235294    2.750668 0.6671351 1.414263    -0.18     2.65
```

**Appendix 2.** Schematic summary of impact of lobster aggregations on the reliability of fishery-independent survey monitoring index (using random stratified sampling method) and fishery-dependent CPUE index (assuming fishers are capable of locating and focusing on aggregations/hotspots) as presented at October 2018 TRLRAG.




Comparison estimating biomass using survey vs CPUE
TRUE Abundance = 16 lobsters total = 1 per area unit
Survey sample 1:
(0+1+3+0)=4 so
average=4/4=1
Abundance =
1*16 = 16
Survey sample 2:
1.2*16 = 19.2
Target aggregations:
(2+3+4)=9 so
average = 9/3 = 3
Abundance =
3*16=48


Comparison estimating biomass using survey vs CPUE
TRUE Abundance = 16 lobsters total = 1 per area unit
Survey sample 1:
(0+1+3+0)=4 so
average=4/4=1
Abundance =
1*16 = 16
Survey sample 2:
1.2*16 = 19.2
Target aggregations:
(2+3+4)=9 so
average = 9/3 = 3
Abundance =
3*16=48
Add areas
Ave=11/5=2.2
Abundance = 35

| TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG) | MEETING 25<br>11-12 December 2018 |
|---|---|
| **REVISION OF DRAFT HARVEST STRATEGY AND CONTROL RULES** | **Agenda Item 5**<br>**For Discussion and Advice** |

## RECOMMENDATIONS

1. That the RAG:
   a. **DISCUSS** and **PROVIDE ADVICE** on the number of years to be averaged in the empirical harvest control rule (eHCR) index and decision rule triggers under the draft Harvest Strategy (**Attachment 5a**).
   b. **NOTE** the next steps for finalising the Harvest Strategy are:
      i. 1) to take any proposed changes into consideration and amend the draft Harvest Strategy;
      ii. 2) send the draft Harvest Strategy to the RAG and Working Group to be endorsed out-of-session; and
      iii. 3) send the draft Harvest Strategy to the PZJA for consideration.

## KEY ISSUES

2. At the last RAG meeting held on 18-19 October 2018, members recommended that in light of the 2017/18 season, the number of years to be averaged in the eHCR index and decision rule triggers be revisited at the next meeting of the RAG prior to finalising the Harvest Strategy.

*eHCR*

3. The eHCR will be used to calculate the recommended biological (RBC), once the draft Harvest Strategy is adopted. The eHCR uses the pre-season survey 1+ and 0+ indices, both standardised catch per unit effort (CPUE) indices (TVH and TIB), applies the natural logarithms of the slopes of the five most recent years' data and includes an upper catch limit of 1,000 tonnes. The relative weightings of the eHCR indices are 70% pre-season survey 1+ index, 10% pre-season survey 0+ index, 10% TIB sector standardised CPUE and 10% TVH sector standardised CPUE.
4. The five year index average was selected by the RAG to limit the variability of the RBC from year to year.
5. Management strategy evaluation (MSE) testing that has been undertaken in developing the eHCR, and this testing can be drawn on to inform discussions. As some parameters have changed since this testing was completed, some simulations will need to be run again. The CSIRO scientific member will provide an update at the meeting on the progress of this work.
6. The RAG is being asked to consider the update from the CSIRO scientific member and where relevant provide advice on the need for further analysis.

*Decision rules*

7. With regards to decision rules, the draft Harvest strategy details that if in any year the pre-season survey 1+ indices is 1.25 or lower (average number of 1+ age lobsters per survey transect) it triggers a stock assessment. If the eHCR limit reference point is triggered in the first year, a stock assessment update must be conducted in March. If after the first year the stock is assessed below the biomass limit reference point, it is optional to conduct a mid-year survey, the pre-season survey must continue annually.

8. At the last RAG meeting, members discussed that given the experience during the 2017/18 season, the mid-year survey trigger may not align with the current expectations of management or industry.

## BACKGROUND

*Harvest Strategy development*

9. The draft TRL Harvest Strategy has been developed in consultation with the RAG over its last few meetings: meeting 18 on 2-3 August 2016; meeting 19 on 13 December 2016 and meeting 20 on 4-5 April 2017).

10. The draft TRL Harvest Strategy was developed to take into account key fishery specific attributes including:

    a. there is potential for large, unpredictable inter-annual variations in availability and abundance of TRL;

    b. TRL is a shared resource important for the traditional way of life and livelihood of traditional inhabitants, commercial and recreational sectors (TRLRAG20 on 4-5 April 2017); and

    c. advice from the RAG industry members to maintain stock abundance at recent levels (2005-2015) (TRLRAG17 on 31 March 2016).

11. The RAG recommended harvest strategy objectives that place greater emphasis on the on the importance of the TRL Fishery for traditional way of life and livelihood of traditional inhabitants. The operational objectives of the Harvest Strategy are to:

    a. Maintain the stock at (on average), or return to, a target biomass point $B_{TARG}$ equal to recent levels (2005-2015) that take account of the fact that the resource is shared and important for the traditional way of life and livelihood of traditional inhabitants and is biologically and economically acceptable.

    b. The agreed $B_{TARG}$ is more precautionary than the default proxy $B_{MEY}$ (biomass at maximum economic yield) level as outlined in the Commonwealth Harvest Strategy Policy and Guidelines 2007 (HSP).

    c. Maintain the stock above the limit biomass level ($B_{LIM}$), or an appropriate proxy, at least 90 per cent of the time.

    d. The agreed $B_{LIM}$ is more precautionary than the default proxy HSP $B_{LIM}$.

    e. Implement rebuilding strategies, if the spawning stock biomass is assessed to fall below $B_{LIM}$ in two successive years.

12. The eHCR uses a regression of the 5 last year's data for the pre-season survey index of abundance of juvenile 1+ TRL (weighting 70%); newly recruited 0+ TRL (weighting 10%); the catch per unit effort (CPUE) indices for the TIB sector (weighting 10%) and CPUE indices for the TVH sector (weighting 10%).

13. The draft HS decision rules are:

    a. <u>Maximum catch limit</u> - The eHCR includes a maximum catch limit of 1000 t. Once the Harvest Streategy is implemented the cap will be reviewed after three years using Management Strategy Evaluation (MSE) testing with the updated stock assessment model.

    b. <u>Pre-season survey trigger</u> - If in any year the pre-season survey 1+ indices is 1.25 or lower (average number of 1+ age lobsters per survey transect) it triggers a stock assessment.

    c. <u>Biomass limit reference point triggered</u> - If the eHCR limit reference point is triggered in the first year, a stock assessment update must be conducted.

    i. If after the first year the stock is assessed below the biomass limit reference point, it is optional to conduct a mid-season survey, the pre-season survey must continue annually.
    ii. If the eHCR limit reference point is triggered two years in a row, a stock assessment must be conducted in December (of the second year).

  d. Fishery closure rules - If the stock assessment determines the stock to be below the biomass limit reference point in two successive years, the TRL Fishery will be closed to commercial fishing.
    i. MSE testing of the eHCR has shown that it is extremely unlikely (<1%) for the Fishery to be closed based on its current performance.

  e. Re-opening the Fishery - Following closure of the Fishery, fishery-independent mid-season and pre-season surveys are mandatory. The Fishery can only be re-opened when a stock assessment determines the Fishery to be above the biomass limit reference point.

  f. Based on the decision rules, there are four alternative possible scenarios that may occur under the application of the eHCR. Graphic representations of the four scenarios were presented to the Working Group.

14. The Fishery is currently operating under an interim Harvest Strategy. The key differences between the interim and draft final Harvest strategy are the use of an eHCR to estimate a recommended biological catch (RBC) annually and the stock assessment model is conducted every three years (rather than annually) to assess the resource status and evaluate the performance of the eHCR. The draft final Harvest Strategy has a number of pre agreed decision rules that are designed to maintain the stock at the agreed target reference point.

15. The TRLWG considered the draft TRL Harvest Strategy at its meeting on 25-26 July 2017 (meeting number 6). Having regard for the comments by members the Working Group:
  a. Recognised that the draft harvest strategy is:
    i. designed to inform management decisions for the Torres Strait TRL Fishery;
    ii. is based on robust fishery independent survey data and stock assessment process;
    iii. treats the TRL Fishery as a single stock;
    iv. does not take into account recreational catches on the basis of TRLRAG advice that catches are likely low; and
    v. has been subject to rigorous performance testing by the TRLRAG.

  b. Recognised that whilst there may be uncertainty in the level of connectivity between the east coast and Torres Strait TRL stocks, the draft TRL harvest strategy uses the best available data including annual fishery independent survey data, to recommend annual total allowable catches. Future work such as the recently funded larval advection modelling project is likely to improve our understanding of stock connectivity overtime.

  c. Requested (Action Item 4) the following be presented at the next TRLWG meeting: a) an overview of the current understanding of stock connectivity between the east coast and the Torres Strait TRL Fishery; and b) the basis for the Queensland east coast TAC.

  d. Recommends that work should continue to examine whether there are cost-effective options for improving estimates of recreational catches in the region.

  e. Recommends that the PZJA work closely with both the Queensland and PNG Governments to ensure complementary management arrangements are adopted in the event that the TRL stock biomass falls below the limit reference point.

f. Recommends that further work be undertaken by the TRLWG and TRLRAG to examine possible options for including social and/or economic objective in the draft Harvest Strategy and applying a management trigger under the harvest strategy as the stock approaches the limit reference point to minimise the impacts on traditional inhabitant commercial fishers.

   i. The RAG was asked to advise on the likely: data and assessment requirements to support the proposed management trigger; impediments, if relevant, to meeting the data and assessment requirements; and, costs of any new data and assessment requirements.

16. At the meeting held on 27-28 March 2018, the RAG agreed that a management trigger can be included that results in alternative management and catch sharing arrangements. However, the trigger level itself and proposed management response needs to be identified by the WG before the RAG can provide advice about how the Harvest Strategy should be modified to accommodate it. The RAG discussed that:

    a. Social and economic limits are often based on tonnage and not % biomass. Biomass based triggers are difficult to monitor and it is not practical for the TRL Fishery given the limitations of available data.

    b. Triggers that result in management changes part way through a season are complex to administer and require real time data and analysis which is expensive for the fishery. In the TRL Fishery in-season adjustments would be difficult under the current inputs.

    c. If a new trigger is incorporated, the Harvest Strategy would need to undergo management strategy evaluation (MSE) testing. This is a costly exercise.

17. The RAG endorsed the draft TRL Harvest Strategy and recommended the WG further discuss and provide the RAG with details on the trigger level and proposed management response.

Australian Government

Australian Fisheries Management Authority

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# GLOSSARY

**Types of reference points:**

| Reference Point | Description |
| --- | --- |
| Metarule | A rule that describes how the RBCs obtained from an assessment should be adjusted in calculating a recommended TAC |
| Target | Relates to a target reference point as per the HSP. Expressed in terms of biomass |
| Limit | Relates to a limit reference point as per the HSP. Fishing stops if this reference point is exceeded a specified number of times. Expressed in terms of biomass |
| MEY | Maximum economic yield occurs when the total profit from the Fishery is maximised |
| MSY | Maximum sustainable yield is the maximum that can be taken from a stock in perpetuity |

**Notation:**

| Notation | Description |
| --- | --- |
| B | Spawning biomass level |
| $B_0$ | The unfished spawning biomass (determined from an appropriate reference point) |
| F | Fishing mortality rate |

**Other acronyms:**

| Acronym | Description |
| --- | --- |
| CPUE | Catch per unit effort |
| HSP | Commonwealth Harvest Strategy Policy and Guidelines 2007 |
| HS | Harvest Strategy |
| HSF | Harvest Strategy Framework |
| HCR | Harvest Control Rule |
| RBC | Recommended Biological Catch |
| TRLRAG | Tropical Rock Lobster Resource Assessment Group |
| TRLWG | Tropical Rock Lobster Working Group |
| TAC | Total Allowable Catch |
| Tiered approach | A framework that uses different control rules to cater for different levels of uncertainty about a stock |
| TIB | Traditional inhabitant boat |
| TVH | Transferrable vessel holder |

# OVERVIEW

The Torres Strait Tropical Rock Lobster Fishery (the Fishery) Harvest Strategy (HS) sets out the management actions needed to achieve the agreed Fishery objectives. The Fishery HS describes the performance indicators used for monitoring the condition of the stock, the fishery-independent survey and stock assessment procedures and the rules applied to determine the recommended biological catch and the notional total allowable catch each fishing season.

The HS uses a single tier approach with an empirical harvest control rule (eHCR) that is used to determine a recommended biological catch (RBC). The eHCR uses the pre-season survey to estimate an index of abundance of juvenile (1+) and newly recruited (0+) TRL and the catch per unit effort (CPUE) indices for the traditional inhabitant boat (TIB) and transferrable vessel holder (TVH) fishing sectors. The RBC is the best available scientific advice on what the total fishing mortality (landings from all sectors and discards) should be for the stock. The RBC is currently used to monitor the performance of the fishery, in future years it will be used to recommend Total Allowable Catches (an enforced limit on total catches).

The HS meets the requirements of the *Commonwealth Fisheries Harvest Strategy Policy and Guidelines 2007 (*HSP) by applying a precautionary approach to the reference points and measures to be implemented in accordance with the reference points. This is reflected in the use of proxy reference points that are more precautionary than those specified in the HSP. The eHCR is designed to decrease exploitation rate as the stock size decreases below the target reference point. The HS uses a biomass target reference point equal to recent levels (2005-2015) that take account of the fact that the resource is shared and important for the traditional way of life and livelihood of traditional inhabitants and is biologically and economically acceptable. The HS proxies are $B_{LIM}$ is 32% of $B_0$, $B_{TARG}$ is 65% of $B_0$.

Further work for the HS will include the development of a tiered approach. The tiered approach applies different types of control rules to cater for different amounts of data available and to account for changes to uncertainty on stock status. A tiered approach adopts increased levels of precaution that correspond to increasing levels of uncertainty about the stock status, in order to maintain the same level of risk across the different tiers.

The status of the stock and how it is tracking against the HS, is reported to the RAG, Torres Strait Tropical Rock Lobster Working Group (the Working Group) and the Protected Zone Joint Authority (PZJA). The stock assessment is conducted periodically to evaluate performance of the eHCR. The stock assessment includes considerations of the catch rates in current and previous fishing seasons, how the catches compare to the RBCs, stock status indicators in relation to the reference points and an RBC for the upcoming fishing season.

# 1 BACKGROUND

This Torres Strait Tropical Rock Lobster Fishery (the Fishery) Harvest Strategy (HS) has been developed in accordance with the *Commonwealth Fisheries Harvest Strategy Policy and Guidelines 2007* (HSP) and consistent with objectives of the *Torres Strait Fisheries Act 1984* (the Act).

The Fishery HS takes into account key fishery specific attributes including:

a) there is potential for large, unpredictable inter-annual variations in availability and abundance of tropical rock lobster (TRL);

b) TRL is a shared resource important for the traditional way of life and livelihood of traditional inhabitants, commercial and recreational sectors (RAG, 4-5 April 2017); and

c) advice from the Tropical Rock Lobster Resource Assessment Group (the RAG) industry members to maintain stock abundance at recent levels (2005-2015) (RAG, 31 March 2016). (NOTE: Working Group advice to be added)

## 1.1 COMMONWEALTH FISHERIES HARVEST STRATEGY POLICY

The objective of the HSP is the sustainable and profitable use of Australia's Commonwealth fisheries in perpetuity through the implementation of harvest strategies that maintain key commercial stocks at ecologically sustainable levels, and within this context, maximise the economic returns to the Australian community.

To meet the HSP objective, harvest strategies are designed to pursue an exploitation rate that keeps fish stocks at a level required to produce maximum economic yield (MEY) and ensure stocks remain above a limit biomass level ($B_{LIM}$) at least 90 per cent of the time. Alternative reference points may be adopted for some stocks to better pursue the objective of maximising economic returns across the Fishery as a whole or other fishery specific objectives.

The HSP provides for the use of proxy settings for reference points to cater for different levels of information available and unique fishery circumstances. This balance between prescription and flexibility encourages the development of innovative and cost effective strategies to meet key policy objectives. Proxies must ensure stock conservation and economic performance as envisaged by the HSP. Such proxies, including those that exceed these minimum standards, must be clearly justified.

With a harvest strategy in place, fishery managers and stakeholders are able to operate with pre-defined rules, management decisions are more transparent, and there are likely fewer unanticipated outcomes necessitating hasty management responses. However, due to the inherently natural variability of TRL abundance there may be a need for significant changes in recommended catch on an annual basis.

## 1.2 DEVELOPMENT OF THE TRL HARVEST STRATEGY

The HS has been developed in consultation with the RAG (meeting no. 18 on 2-3 August 2016; meeting no. 19 on 13 December 2016 and meeting no. 20 on 4-5 April; 2017). The HS has been endorsed by the Working Group meeting no. X on 25-26 July 2017. This HS replaces the interim HS developed for the Fishery in 2008 .(Attachment A).

NOTE: TRLWG advice to be provided once TRLRAG advice finalised – this statement is to be updated as required.

# 2 TRL FISHERY HARVEST STRATEGY

## 2.1 SCOPE

This HS applies to the whole fishery and it takes into account catch sharing arrangements between Australia and Papua New Guinea (PNG).

The HS outlines the control rules used to develop advice on the recommended biological catch (RBC) and in future years it will be used to recommend Total Allowable Catches (an enforced limit on total catches)[1]. The HS sets the criteria that pre-agreed management decisions will be based on in order to achieve the Fishery objectives.

Overtime the HS may be amended to use a tiered approach to cater for different amounts of data available and different types of assessments (for example mid-year surveys and annual assessments). Underpinning a tiered HS is increased levels of precaution with increasing levels of uncertainty about the stock status. Each tier has its own harvest control rule (HCR) and associated rules that are used to determine a RBC.



## 2.2 OBJECTIVES

The operational objectives of the Harvest Strategy are to:

a) Maintain the stock at (on average), or return to, a target biomass point $B_{TARG}$ equal to recent levels (2005-2015) that take account of the fact that the resource is shared and important for the traditional way of life and livelihood of traditional inhabitants and is biologically and economically acceptable.

   - The agreed $B_{TARG}$ is more precautionary than the default proxy $B_{MEY}$ (biomass at maximum economic yield) level as outlined in the Commonwealth Harvest Strategy Policy and Guidelines 2007 (HSP).

b) Maintain the stock above the limit biomass level ($B_{LIM}$), or an appropriate proxy, at least 90 per cent of the time.

   - The agreed $B_{LIM}$ is more precautionary than the default proxy HSP $B_{LIM}$.

[1] The total allowable catch (TAC) for the Fishery is currently notional and is not used to control harvest. It is used to inform catch sharing arrangements with Papua New Guinea and to inform the status of the stock.

c) Implement rebuilding strategies, if the spawning stock biomass is assessed to fall below $B_{LIM}$ in two successive years.

## 2.3 RECOMMENDING TACs FROM RBCs

The Recommended Biological Catch (RBC) is the recommended total catch of TRL (both retained and discarded) that should be taken by all sectors of the Fishery. The HSP states that when setting the TAC for the next fishing season the HS should take into account all sources of fishing mortality.

The HS does not include catches taken by non-commercial fishing sectors, for example traditional, recreational or research catches. The RAG recommended at Meeting No.18 on 2-3 August 2016 that non-commercial catches should not be accounted for, because the overall catches are likely to be relatively low and there would be limited impact on the stock assessment. The HS may be updated in the future to account for changing circumstances in the Fishery, the review provisions are described in **Section 2.13**.

*The total allowable catch (TAC) for the Fishery is currently notional (not enforced) and is not used to control harvest. It is used to inform catch sharing arrangements with Papua New Guinea and to inform the status of the stock.*

## 2.4 MONITORING

Biological data for the Fishery are monitored by a range of methods listed below. Currently there is no ongoing monitoring strategy in place to collect economic information.

**Fishery independent surveys**

A key component of the monitoring program is the fishery-independent survey which provides a time-series of relative abundance indices for TRL. Fishery-independent surveys have been conducted in the Fishery since 1989. Historically (1989-2014), mid-season (July) surveys focused on providing an index of abundance of the spawning (age 2+) and juvenile (age 1+) lobsters. Mid-season surveys have been replaced with pre-season (November) surveys (2005-2008; 2014 to current) which focus on providing an index of recruiting (age 1+) lobsters as close as possible to the start of the fishing season to support the transition to quota management and setting of a TAC. Pre-seasons surveys also provide indices of recently-settled (age 0+) lobsters, which may become useful under quota management as they allow forecasting of stock one year in advance.

**Catch and effort information**

Fishers in the transferrable vessel holder (TVH) sector are required to record catch and effort information in the Torres Strait Tropical Rock Lobster Daily Fishing Log (TRL04). The following data are recorded for each TVH fishing operation: the port and date of departure and return, fishing area, fishing method, hours fished and the weight (whole or tails) of TRL retained. Fishers in the traditional inhabitant boat (TIB) sector voluntarily report catch and effort information to buyers and processors who record the information in the Torres Strait Seafood Buyers and Processors Docket Book (TDB01). Some processors previously (2014-2016) reported aggregate TIB catch information directly to AFMA, these processors are currently reporting with the TDB01 docket book.

## 2.5 INTEGRATED STOCK ASSESSMENT MODEL

The stock assessment model (termed the ‘Integrated Model’) (Plagányi *et al.* 2009) was developed in 2009 and is an Age-Structured Production Model, or Statistical Catch-at-Age Analysis (SCAA) (e.g. Fournier and Archibald 1982). It is a widely used approach for providing RBC advice and the associated uncertainties.

The model integrates all available information into a single framework to assess resource status and provide a RBC. The model addresses all of the concerns highlighted in a review of the previous stock assessment approach (Bentley 2006, Ye *et al*. 2006, 2007). The model is fitted to the mid-season and pre-season survey data and TIB and TVH CPUE data. The growth relationships used in the model were revised from the previous stock assessment model (Ye *et al*. 2006) to ensure that the modelled individual mass at age more closely resembled field measurements. The model is compatible as an Operating Model in a Management Strategy Evaluation (MSE) framework to support the management of the Fishery.

The stock assessment model is non-spatial and assumes that the Torres Strait Tropical Rock lobster Fishery stock is independent of the Queensland East Coast Tropical Rock Lobster Fishery stock. A spatial version of the model has been developed as part of an earlier MSE project, and can be used to investigate plausible linkages between these stocks (Plagányi *et al*. 2012, 2013).

The model includes three age-classes only (0+, 1+ and 2+ age lobsters) as it is assumed that lobsters migrate out of Torres Straits in October each year. Torres Strait TRL emigrate in spring (September-November) and breed during the subsequent summer (November-February) (MacFarlane and Moore 1986; Moore and Macfarlane 1984). A Beverton-Holt stock-recruitment relationship is used (Beverton and Holt 1957), allowing for annual fluctuation about the average value predicted by the recruitment curve. The model is fitted to the available abundance indices by maximising the likelihood function. Quasi-Newton minimisation is used to minimise the total negative log-likelihood function (using the package AD Model Builder™) (Fournier *et al*. 2012).

## 2.6 EMPIRICAL HARVEST CONTROL RULE

The empirical harvest control rule (eHCR) recommended by the RAG uses the pre-season survey 1+ and 0+ indices, both standardised CPUE indices (TVH and TIB), applies the natural logarithms of the slopes of the five most recent years' data and includes an upper catch limit of 1,000 t. The relative weightings of the eHCR indices are 70 per cent pre-season survey 1+ index, 10 per cent pre-season survey 0+ index, 10 per cent TIB sector standardised CPUE and 10 per cent TVH sector standardised CPUE.

The basic formula is:

$$RBC_{y+1} = wt\_s1 \cdot \left(1 + s_y^{presurv,1}\right) \cdot \bar{C}_{y-4,y} + wt\_s2 \cdot \left(1 + s_y^{presurv,0}\right) \cdot \bar{C}_{y-4,y} + wt\_c1 \cdot \left(1 + s_y^{CPUE,TVH}\right) \cdot \bar{C}_{y-4,y} + wt\_c2 \cdot \left(1 + s_y^{CPUE,TIB}\right) \cdot \bar{C}_{y-4,y}$$

Or if $RBC_{y+1}$ > 1000t, $TAC_{y+1}$ = 1000.

Where:

$\bar{C}_{y-4,y}$ is the average achieved catch during the past 5 years, including the current year i.e. from year *y*-4 to year *y*,

$s_y^{presurv,1}$ is the slope of the logarithms of the preseason survey 1+ abundance index, based on the 5 most recent values;

$s_y^{presurv,0}$ is the slope of the logarithms of the preseason survey 0+ abundance index, based on the 5 most recent values;

$s_y^{CPUE,TVH}, s_y^{CPUE,TIB}$ is the slope of the logarithms of the TVH and TIB CPUE abundance index, based on the 5 most recent values;

wt_s1, wt_s2, wt_c1, wt_c2 are tuning parameters that assign relative weight to the preseason 1+ (wt_s1) and 0+ (wt_s2) survey trends compared with the CPUE TVH (wt_c1) and TIB (wt_c2) trends.

## 2.7 REFERENCE POINTS

The HS reference points are:

a) The unfished biomass $B_0$ is the model-estimate of spawning stock biomass in 1973 (start of the Fishery). $B_0 = B_{1973}$.

b) The target biomass $B_{TARG}$ is the spawning biomass level equal to recent levels (2005-2015) that take account of the fact that the resource is shared and important for the traditional way of life and livelihood of traditional inhabitants and is biologically and economically acceptable. $B_{TARG}$ is the proxy for $B_{MEY}$, $B_{TARG} = 0.65\ B_0$.

- The agreed $B_{TARG}$ is more precautionary than the default proxy $B_{MEY}$ (biomass at maximum economic yield) level as outlined in the (HSP). The RAG noted a $B_{TARG}$ higher that the HSP default was considered important for the Fishery because: 1) the stock: is a shared resource that is particularly important for traditional fishing; 2) the stock has high variability; and, 3) all industry members recommended the HS maintain the stock around the relatively high current levels (RAG meeting no. 17, 31 March 2016 and meeting no. 18, 2-3 August 2016).

c) The limit biomass $B_{LIM}$ is the spawning biomass level below which the risk to the stock is unacceptably high and the stock is defined as 'overfished'. $B_{LIM}$ is agreed to be half of $B_{TARG}$, $B_{LIM} = 0.32\ B_0$.

- The agreed $B_{LIM}$ is more precautionary than the default proxy HSP $B_{LIM}$.

d) If the limit reference point ($B_{LIM}$) is triggered in two successive years then the Fishery is closed.

e) The target fishing mortality rate $F_{TARG}$ is the estimated level of fishing mortality rate that maintains the spawning biomass around $B_{TARG}$. $F_{TARG} = 0.15$.

- $F_{TARG} = 0.15$ is the target fishing mortality rate that corresponds to an optimal level in terms of economic, biological and social considerations (RAG meeting no. 18, 2-3 August 2016).

***Rational for reference points***

The HSP recognises that each stock/species/fishery will require an approach tailored to the fishery circumstances, including species characteristics. The HSP identifies that for highly variable stocks that may naturally (in the absence of fishing) breach $B_{LIM}$, the default reference point proxies may not be appropriate. The HSP states 'with highly variable species it is important to develop a harvest strategy that meets the intent of the HSP.' Further, 'stocks that fall below $B_{LIM}$ due to natural variability will still be subject to the recovery measures stipulated in the HSP.' A number of adaptive management approaches may be used to deal with this, such as pre-season surveys to provide estimates of abundance to which the eHCR is applied.

The Fishery is characterised by a highly variable stock where majority of the catch (since 2001 due to the introduction of a minimum size limit) is from a single cohort. The stock assessment model and MSE testing have identified the target biomass should be set between 65 and 80 per cent of the unfished biomass to account for the importance of the stock for the traditional way of life and livelihood of traditional inhabitants and to achieve biological and economic objectives. The HS higher average target biomass level, compared to the default HSP target of 0.48 per cent of unfished biomass, reduces the risk of recruitment being compromised.

The unfished biomass ($B_0$) is calculated within the stock assessment model, the value of unfished biomass and target biomass have therefore varied over time in response to annual data updates and model parameter settings and estimates. Estimates of unfished biomass and target biomass are particularly sensitive to changes to parameter *h*, which determines the steepness of the stock-recruit relationship, and the input parameter that controls the level of stock-recruit variability.

Independent of variability to the unfished biomass value, the target fishing mortality rate $F_{TARG}$ =0.15 is applied to maintain the spawning biomass around the biomass target reference point ($B_{TARG}$), which is the average level over the past two decades. This is assumed to be a proxy for $B_{MEY}$ because stakeholders agreed that this target level corresponded to an optimal level in terms of economic, biological and social considerations (TRLRAG meeting no. 18, 2-3 August 2016).

The biomass limit reference point ($B_{LIM}$) is 32 per cent of unfished biomass. The higher limit reference point, compared to the HSP proxy of 20 per cent of unfished biomass, is supported by recommendations of similar limit reference points for other highly variable species such as forage fish (Pikitch *et al.* 2012). Due to the changing values of unfished biomass and target biomass the value of the limit reference point, taken as half the target reference point, has previously varied between 32 and 40 per cent of unfished biomass.

Recent MSE testing identified that a limit reference point of 40 per cent unfished biomass is too conservative, it would result in the limit reference point being breached more frequently and add unnecessary precautionary to the HS The RAG agreed to set the limit reference point at 32 per cent of unfished biomass with the condition that if the stock falls below the limit reference point in two successive years it triggers a Fishery closure. The eHCR is more precautionary than the HSP criterion to 'ensure that the stock stays above the limit biomass level at least 90 per cent of the time.' The HSP states that for highly variable species the risk criterion can be amended to increase the frequency the limit reference point may be breached or by altering the reference point value.

## 2.8 eHCR AND STOCK ASSESSMENT CYCLE

The eHCR and stock assessment cycle is as follows:

- The eHCR is run in November each year to provide a RBC by 1 December for the following fishing season.
- A stock assessment is run on a three year cycle in March, unless the stock assessment is triggered by a decision rule **(Section 2.10)**. The stock assessment determines the Fishery stock status and evaluates the performance of the eHCR and identifies if any revisions to the eHCR are required.
- If the eHCR needs to be revised, the stock assessment is conducted annually to estimate the RBC until the revised eHCR is agreed.

## 2.9 DATA SUMMARY

The annual data summary reviews the nominal and standardised catch per unit effort (CPUE) from the TIB and TVH sectors, as well as total catch from all sectors, the size-frequency information provided from a sub-sample of commercially caught TRL and the fishery-independent survey indices of +0 and +1 age lobsters. The data summary is used as an indicator to identify if catches correspond to the RBC, and to monitor CPUE.

## 2.10 DECISION RULES

The decision rules for the Fishery Harvest Strategy are:

**Maximum catch limit**

- The eHCR includes a maximum catch limit of 1000 t. Once the HS is implemented the cap will be reviewed after three years using MSE testing with the updated stock assessment model.

**Pre-season survey trigger**

- If in any year the pre-season survey +1 indices is 1.25 or lower (average number of +1 age lobsters per survey transect) it triggers a stock assessment.

**Biomass limit reference point triggered**

- If the eHCR limit reference point is triggered in the first year, a stock assessment update must be conducted in March.
    - If after the first year the stock is assessed below the biomass limit reference point, it is optional to conduct a mid-season survey, the pre-season survey must continue annually.
- If the eHCR limit reference point is triggered two years in a row, a stock assessment must be conducted in December (of the second year).

**Fishery closure rules**

- If the stock assessment determines the stock to be below the biomass limit reference point in two successive years, the Fishery will be closed to commercial fishing.
    - Management strategy evaluation (MSE) testing of the eHCR has shown that it is extremely unlikely (<1%) for the Fishery to be closed based on its current performance.

**Re-opening the Fishery**

- Following closure of the Fishery, fishery-independent mid-season and pre-season surveys are mandatory. The Fishery can only be re-opened when a stock assessment determines the Fishery to be above the biomass limit reference point **(Attachment A, Figure 5)**.

Based on the decision rules, there are four alternative possible scenarios **(Section 2.11)** that may occur under the application of the eHCR. Graphic representations of the four scenarios are provided in **Attachment A**.

## 2.11 DECISION RULE SCENARIOS

**Scenario 1 – eHCR limit not breached and the eHCR does not require revision**

- The eHCR assesses the Fishery to be above the biomass limit reference point.
- The eHCR RBCs appear to remain within ranges tested by management strategy evaluation (MSE).
- The updated stock assessment does not indicate any need for revision of the HCR.
- Application of the eHCR continues unchanged.
- A graphic representation of Scenario 1 is provided in **Attachment A, Figure 1**.

**Scenario 2 – eHCR limit not breached, eHCR and stock assessment require revision**

- The eHCR assesses the Fishery to be above the biomass limit reference point.
- The eHCR RBCs appear to remain within ranges tested by MSE.
- The updated stock assessment indicates the eHCR recommended TACs are outside the revised ranges tested by MSE, indicating that the eHCR should be revised.
- Annual RBCs need to be set using annual stock assessments until a revised eHCR has been agreed, after which the revised eHCR is applied.

A graphic representation of Scenario 2 is provided in **Attachment A, Figure 2**.

**Scenario 3– limit is breached, eHCR is reviewed by stock assessment and the limit is not breached**

- The eHCR assesses the Fishery to be below the biomass limit reference point in one year.
- A stock assessment update (March) is required to confirm if the limit has indeed been breached. This assessment update determines that the limit has not been breached.
- If the biomass limit reference point is breached once, discussions will be held on preventative measures to reduce the risk of closure.
- The eHCR RBC is applied and consideration is given to revising the eHCR to prevent future incorrect triggering of the biomass limit reference point.
- The stock assessment continues on a three year cycle, unless triggered to occur by a decision rule.
- A graphic representation of Scenario 3 is provided in **Attachment A, Figure 3**.

**Scenario 4 – limit is breached, stock assessment confirms the limit is breached**

- The eHCR assesses the Fishery to be below the biomass limit reference point in two successive years.

- A stock assessment update (March) is required to confirm if the limit has been breached. This assessment update determines that the limit has been breached.

- The eHCR assesses the Fishery to be below the biomass limit reference point for a second successive year.

- A second stock assessment update (December) is required to confirm whether the trigger has been breached a second time. This assessment update determines that the limit has been breached a second time.

- The commercial fishery is closed until an assessment update confirms that the stock has recovered to above the limit.

    - If the Fishery is closed to commercial fishing, discussions are held on future management arrangements.
    - Fishery independent mid-season and pre-season surveys are mandatory and conducted on an annual basis. The Fishery will only re-open when the Fishery is assessed to be above the biomass limit reference point by the stock assessment.
    - The eHCR must be revised before being re-implemented to reduce the risk of the Fishery breaching the biomass limit reference point and for the eHCR to incorporate rebuilding requirements.

- A graphic representation of Scenario 4 is provided in **Attachment A, Figure 4**.



## 2.12 GOVERNANCE

The status of the Fishery and how it is tracking against the HS is reported to the RAG, Working Group and the PZJA as part of the yearly RBC and TAC setting process.

## 2.13 REVIEW

Under certain circumstances, it may be necessary to amend the harvest strategy. For example if:

- there is new information that substantially changes the status of a fishery, leading to improved estimates of indicators relative to reference points; or

- drivers external to management of the fishery increase the risk to fish stock/s; or

- it is clear the strategy is not working effectively and the intent of the HSP is not being met; or

- alternative techniques are developed (or a more expensive but potentially more cost-effective harvest strategy that includes mid-year surveys and annual assessments is agreed) for assessing the Fishery. The HSF may be amended to incorporate decision rules appropriate for those assessments.

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# Testing an alternative empirical harvest control rule for the Torres Strait *Panulirus ornatus* tropical rock lobster fishery

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## EXTENDED SUMMARY

An empirical harvest control rule (eHCR) for Torres Strait tropical lobster *Panulirus ornatus* was developed to achieve defined biological, economic and socio-cultural objectives for the lobster fishery. A key principle is that fishery managers, fishers and key stakeholders utilise pre-agreed and pre-tested rules to adjust management recommendations given updates of data. The performance of eHCR alternative candidates is evaluated using four alternative Operating Models, with 200 stochastic replicates each and 800 total simulations, accounting for observation error and implementation uncertainty. The eHCR adjusts recommended biological catches relative to a recent average, based predominantly on the logarithm of the slopes of recent trends in the pre-season recruiting lobster, with lower weighting accorded to trends in recently-settled lobster and CPUEs from two fishing sectors. In addition, a

maximum catch limit of 1000t is set. The eHCR formula thus uses recent trends in survey and CPUE information to implement rapid but precautionary short-term adjustments needed to effectively manage a highly variable fishery.

The eHCR selected by the TRLRAG stakeholders uses weightings of 70% for the Preseason 1+ index, and 10% for each of the other three indicators. The Preseason 1+ index is the most reliable and direct in terms of indexing the biomass of lobsters that will be available to be caught in the next fishing season, and hence this index is assigned the highest weighting of 70%. The Preseason 0+ index provides an early indication of the following year's recruitment, whereas the CPUE indices reflect the abundance of the large 2+ lobsters, the survivors of which will migrate out of the Torres Strait to spawning grounds to the East, and hence they index spawning biomass which is an important consideration in terms of ensuring the future sustainability of the stock. Each of these three secondary indices (Survey 0+ and CPUE (TIB and TVH)) are assigned a weighting of 10% in the eHCR formula. Simulation testing showed that the best approach is to use the slope of the trends in the secondary indices over the last five years' data (after first taking the natural logarithm of the data) for each of the abundance indices. This allows the Recommended Biological Catch (RBC) to be based on medium term trends in abundance, rather than on just the current abundance. Using the last five years' data gave the best performance in terms of a number of key statistics that were used to compare the performance of alternative candidate rules. Key performance statistics considered by the TRLRAG included those related to resource status (spawning biomass level, and levels relative to target reference levels), average annual catch (averaged over 20 years), average annual variability in catch, as well as risk to the fishery and risk of closure of the fishery. The eHCR candidate that included taking the natural logarithm was preferred because this has the effect of dampening some of the inter-annual variability and hence ensuring that the RBC responds to medium-term changes in resource trends rather than moving up or down very erratically. Similarly, a number of alternative options were explored that used the trend fitted to different numbers of years of historical abundance indices, however using the trend based on the past 5 years was shown to perform best.

The TRLRAG requested seeing an alternative version of the eHCR that uses the slope of the past three years' data instead. This document therefore presents results from re-testing a rule equivalent to the 5 year rule but with a 3 year slope tested. For comparative purposes, an example is also provided using 3-year slope averages in combination with catch averaged over 3 years rather than 5. The use of a 3 year slope in combination with a 3 year catch average did not however perform satisfactorily as the biomass declines over time, and hence it is recommended that this rule not be explored further. The alternative 3-year rule with 5 year catch average performed reasonably though. The main trade-off is that, as expected, the catch variability is much greater, hence for example in general the RBC will be lower or higher each year than the more dampened 5-year rule. Simulations also suggest that the average catch will be slightly less using this rule than the 5-year rule, and these trade-offs (see summary plot below) will be discussed at the forthcoming TRLRAG meeting.

Applying the 5-year and 3-year eHCR rules to available data in 2018 yields respective RBCs of 500t and 693t. Note that the comparable estimates for 2017 was 519t (noting this value was uncertain as there wasn't yet a continuous 5-year survey series available) and 287t.

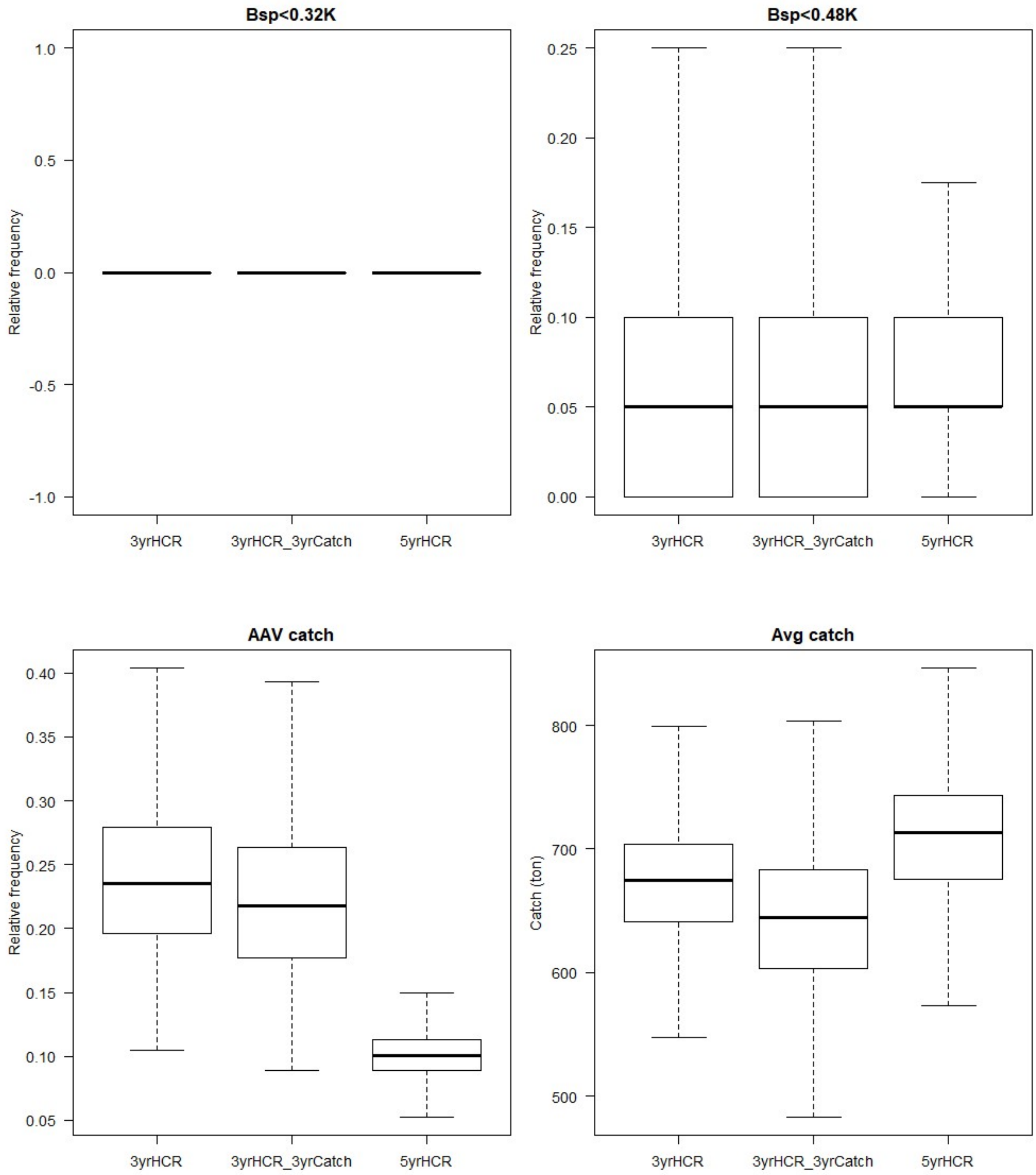



Figure: Summary of key statistics when comparing 3 alternative eHCRS. Comparison of some key performance statistics for final set of eHCRs. Plots show the probability of depletion below each of two reference levels, $B_{LIM}$ = 0.32K and precautionary level 0.48K limit reference point, together the Average Annual Variability (AAV) of catch, and total annual catch (t). The central line shows the median, the box the $75^{th}$ and $25^{th}$ percentiles and the whiskers represent the full range of projected values excluding outliers.

## INTRODUCTION

The TRL stock is naturally highly variable and the fishery focuses largely on a single 2 year old age-class only. A Recommended Biological Catch (RBC) needs to be set annually in such a way as to ensure biological and economic sustainability consistent with the principles of the Australian Commonwealth Harvest Strategy as well as the TRL fisheries and Protected Zone Joint Authority (PZJA) objectives. For this reason, an annual pre-season survey of one-year old recruits is conducted as close to the start of the fishing season as possible (November) to inform on the likely biomass of the fishable cohort the next year. This information together with all other sources of information and data for the fishery have in the past been input to an integrated stock assessment model that was used to set the RBC. However, there is insufficient time following the pre-season survey for the relevant management groups to review the stock assessment update annually, and hence an alternative approach has been recommended.

The new approach uses an empirical (data-based) Harvest Control Rule (eHCR) that can be rapidly applied to provide a RBC once the catch, survey indices and other data inputs (CPUE or Catch-Per-Unit-Effort) become available. The eHCR is a central component of a new harvest strategy that is under development for this fishery. Australia's Commonwealth Harvest Strategy Policy (HSP) defines harvest strategies as "a framework that specifies the pre-determined management actions in a fishery necessary to achieve the agreed ecological, economic and/or social management objectives." A key principle is that fishery managers, fishers and key stakeholders utilise pre-agreed (and preferably pre-tested) rules to adjust management recommendations given updates of data and/or model outputs (HSP) (http://www.agriculture.gov.au/fisheries/domestic/harvest_strategy_policy).

Management Strategy Evaluation (MSE) (Butterworth & Punt 1999, Smith et al. 2007, Dankel & Edwards 2016) has been used to evaluate approaches for setting Total Allowable Catches (TACs) for several rock lobster resources, including in Australia (Punt & Hobday 2009, Punt et al. 2012), New Zealand (Starr et al. 1997) and South Africa (Johnston & Butterworth 2005). In Australia, the decision rule (or harvest control rule) for southern rock lobster in South Australia's southern zone, is based on changes in catch rates, with the aim of maintaining constant exploitation rates.

This paper describes the results of applying MSE to evaluate an alternative eHCR for the Torres Strait *P. ornatus* fishery, using a 3-year slope average rather than 5-year slope average.

**METHODS**

For Reference purposes the methods are shown in the Appendix and are an extract from Plagányi et al. (2018). The identical methods were used for the additional two evaluations done, except that in the first instance the slopes of the indices were computed using the latest 3 years' data and in the second instance this was combined with reducing computation of the average catch from 5 to 3 years.

**RESULTS**

Results are shown in Figures 1-6, and can be compared with earlier results shown in Appendix Figs A.1-A.5.

Applying the 5-year and 3-year eHCR rules to available data in 2018 yields respective RBCs of 500t and 693t. Note that the comparable estimates for 2017 was 519t (noting this value was uncertain as there wasn't yet a continuous 5-year survey series available) and 287t.

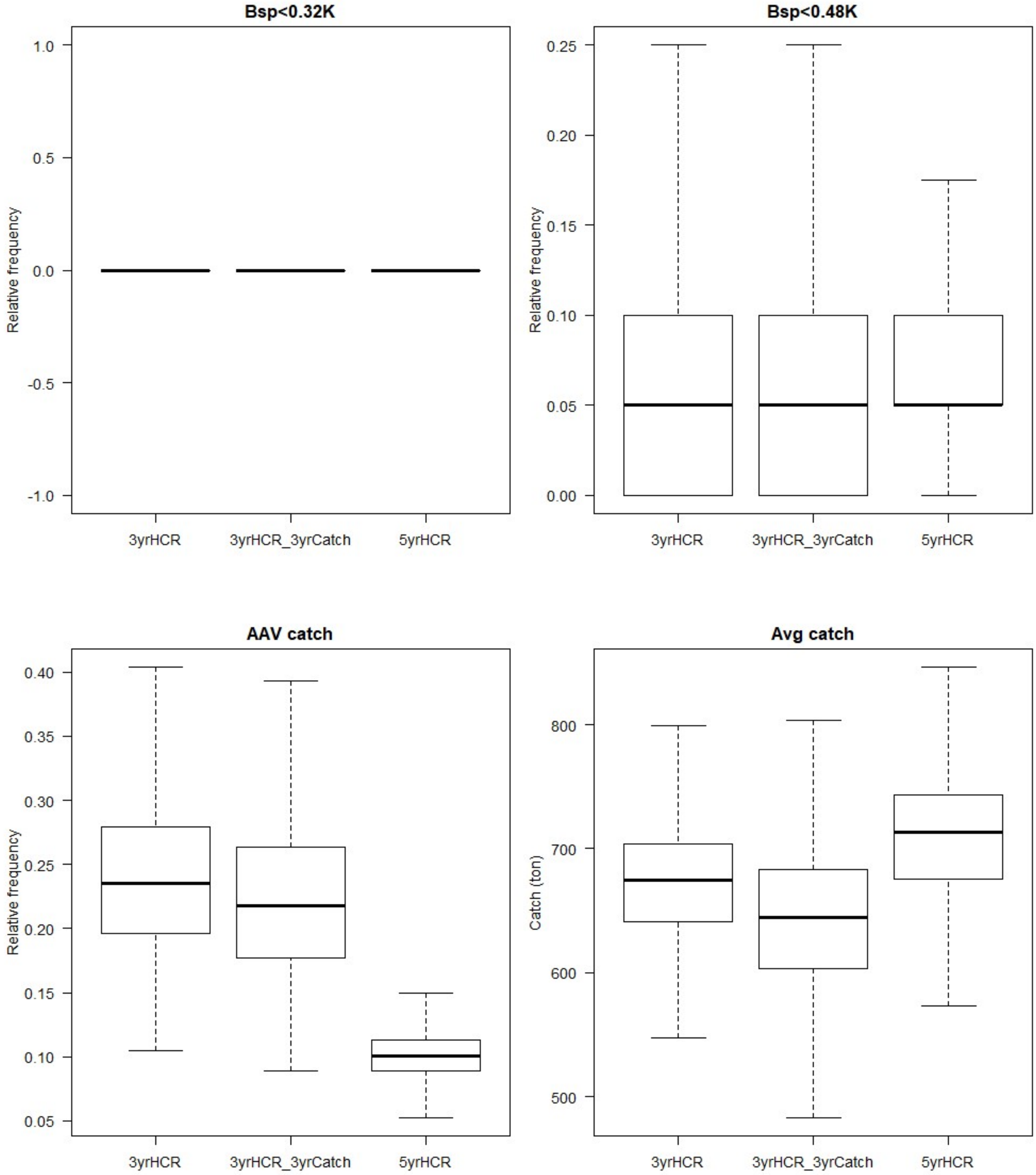



Fig. 1. Comparison of some key performance statistics for final set of eHCRs. Plots show the probability of depletion below each of two reference levels, $B_{LIM}$ = 0.32K and precautionary level 0.48K limit reference point, together the Average Annual Variability (AAV) of catch, and total annual catch (t). The central line shows the median, the box the 75th and 25th percentiles and the whiskers represent the full range of projected values excluding outliers.

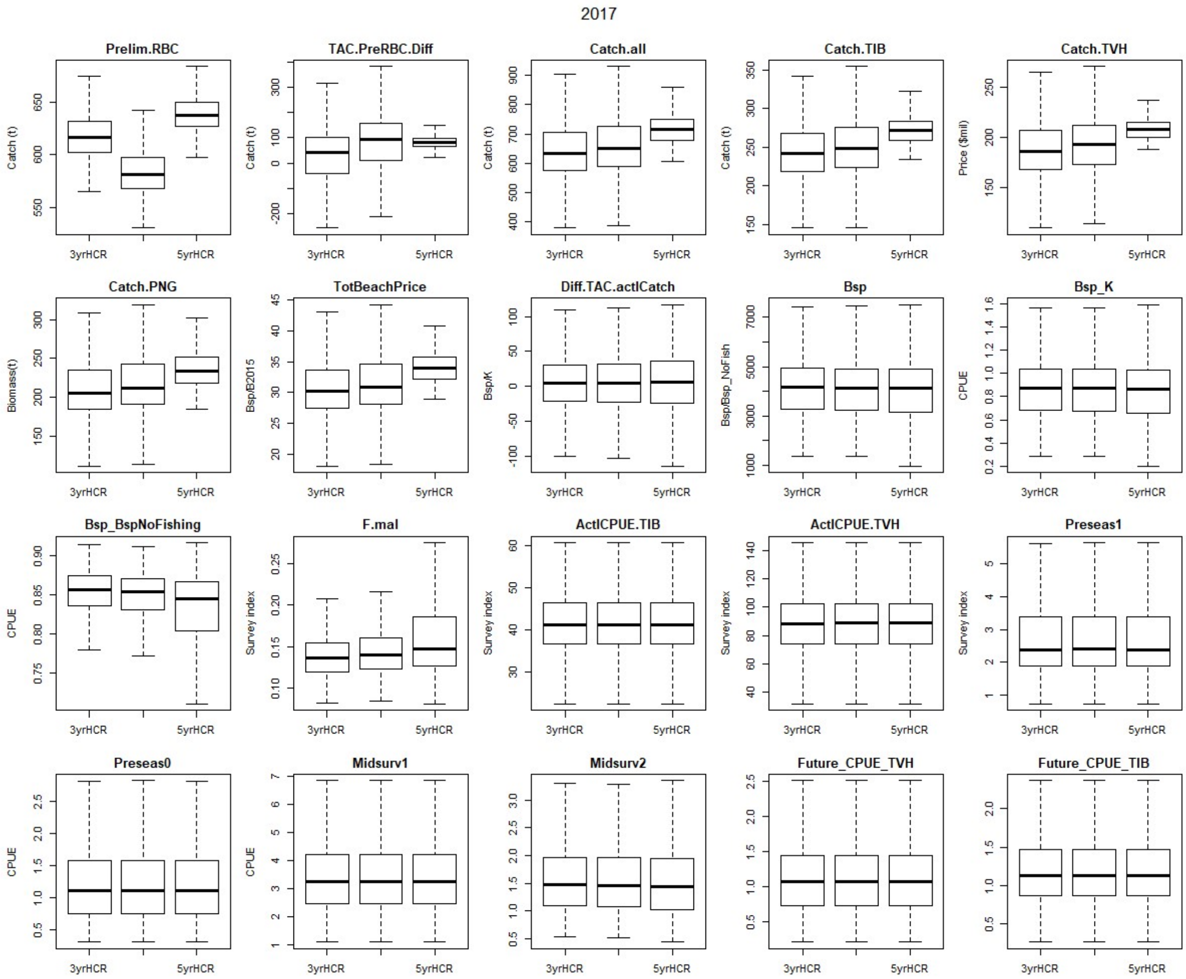
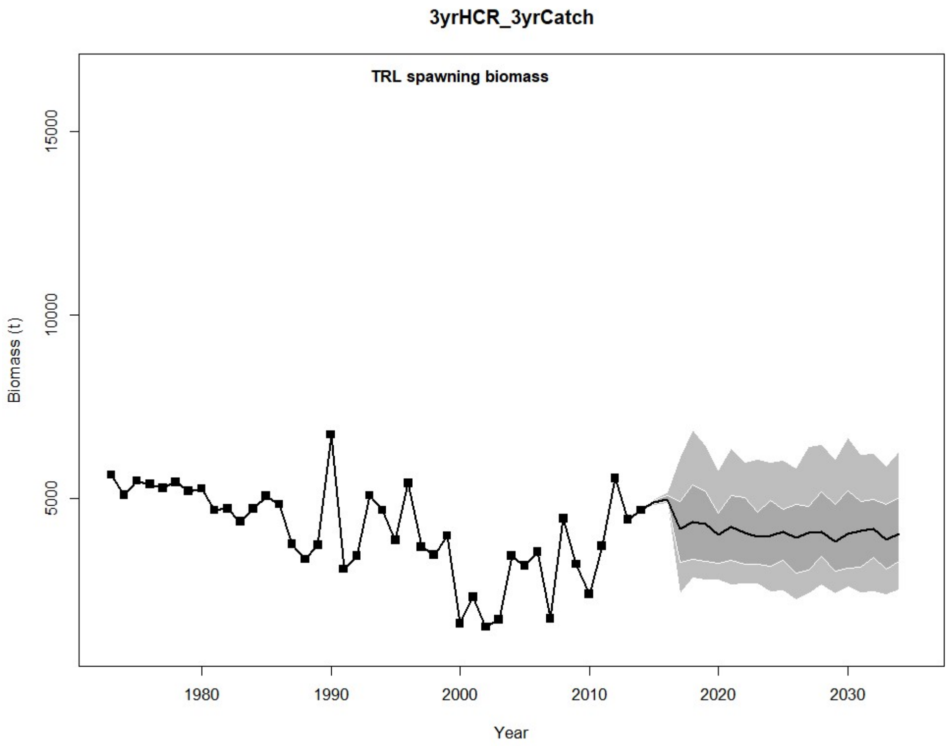



Fig. 2. Comparison of performance statistics for eHCRs of 3yrHCR, 3yrHCR_3yrCatch and 5yrHCR.



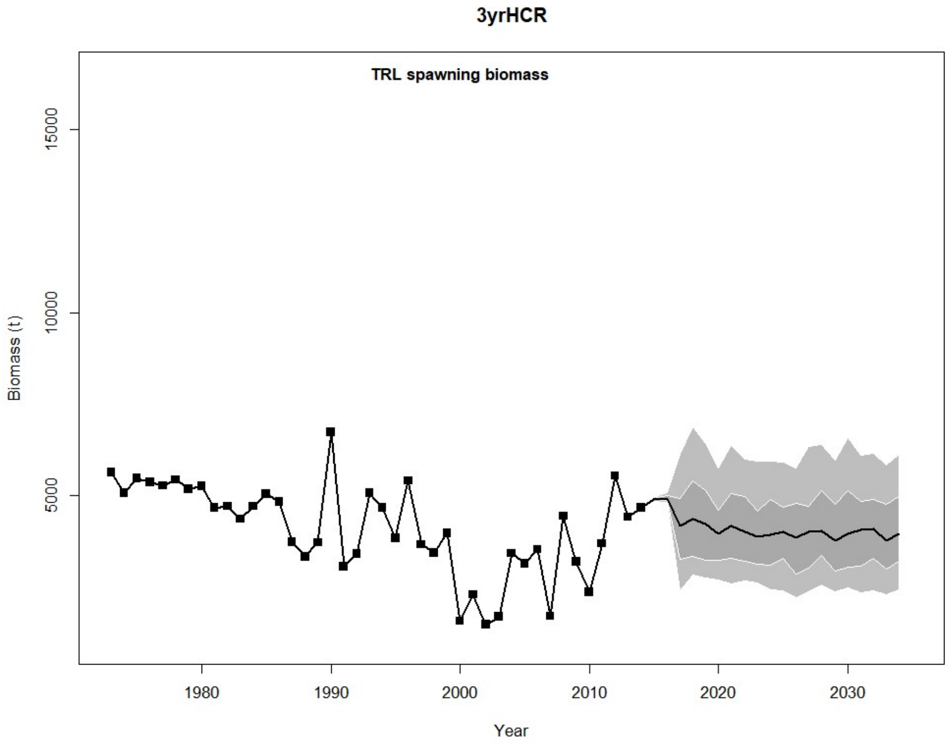




Fig. 3. Distributions (solid line: median, 50% intervals: dark shaded area, 80% intervals: light shaded area) of future projected spawning biomass with historic values and when using the eHCR 3yrHCR_3yrCatch (Upper plot) and 3yrHCR (Lower plot).

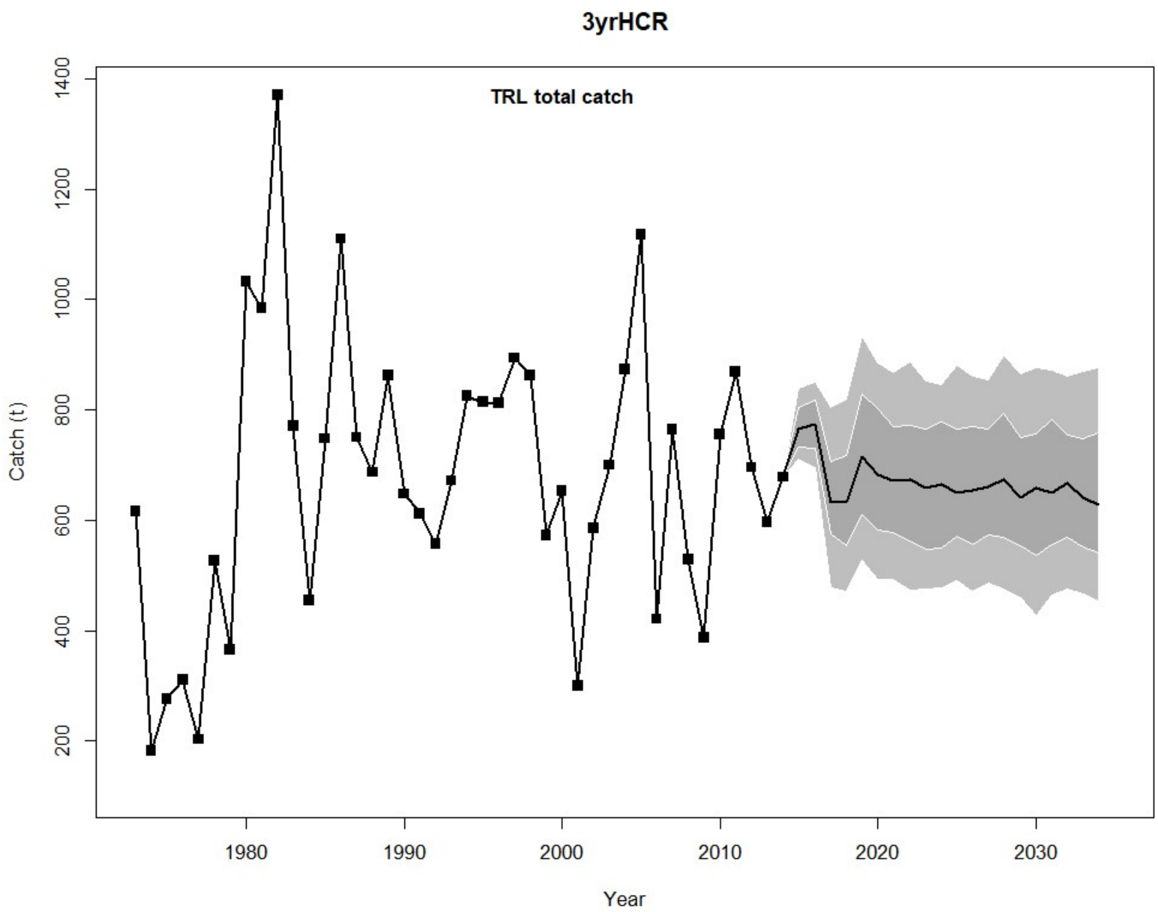



Fig. 4. Distributions (solid line: median, 50% intervals: dark shaded area, 80% intervals: light shaded area) of future projected total catch (t) for TRL compared with historic values and when using the eHCR 3yrHCR.

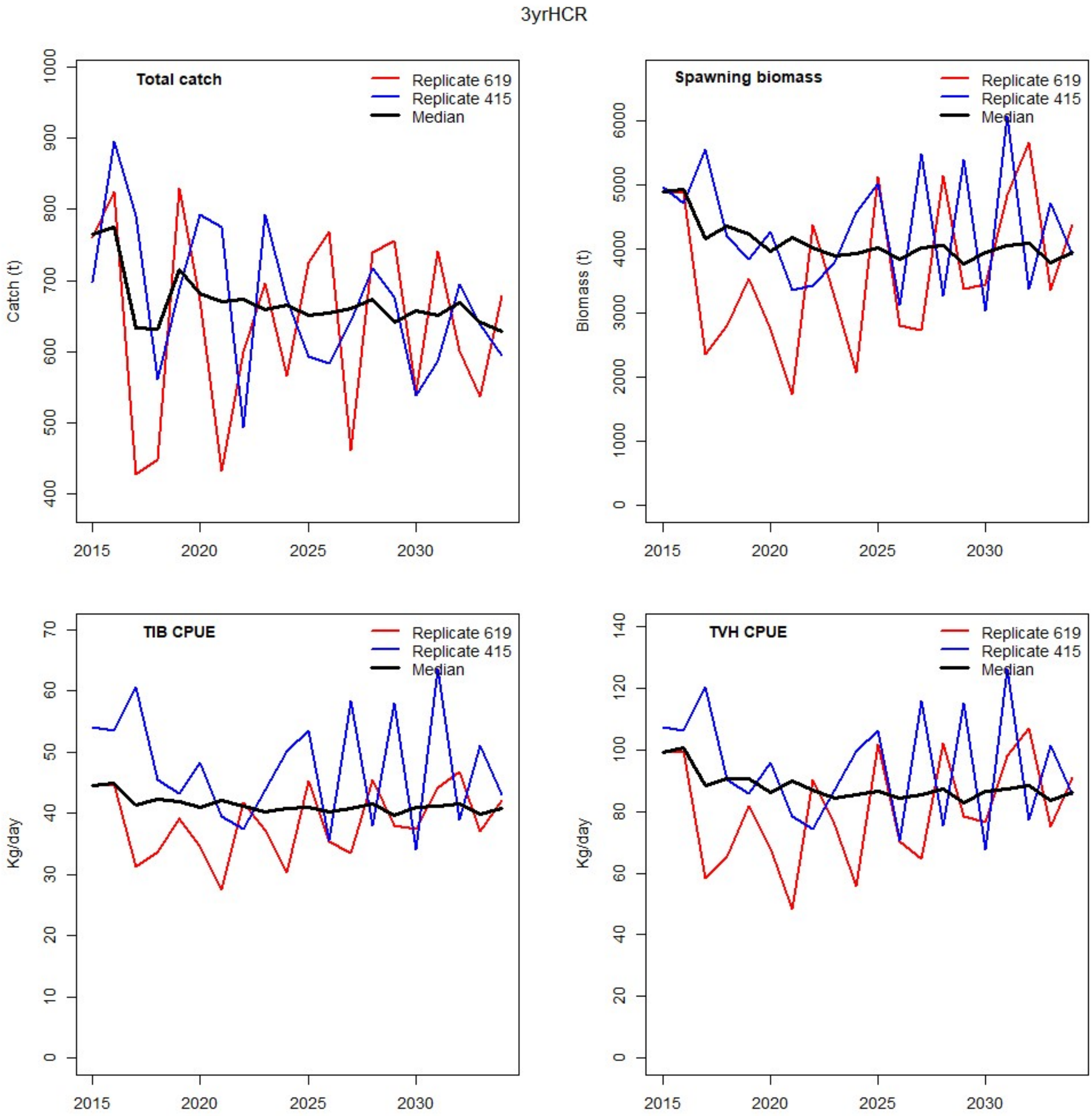



Fig. 5. Worm plots showing two randomly selected individual trajectories compared with the median values of total catch and spawning biomass (top panels) and projected CPUE for the two sectors TIB and TVH (bottom panel).

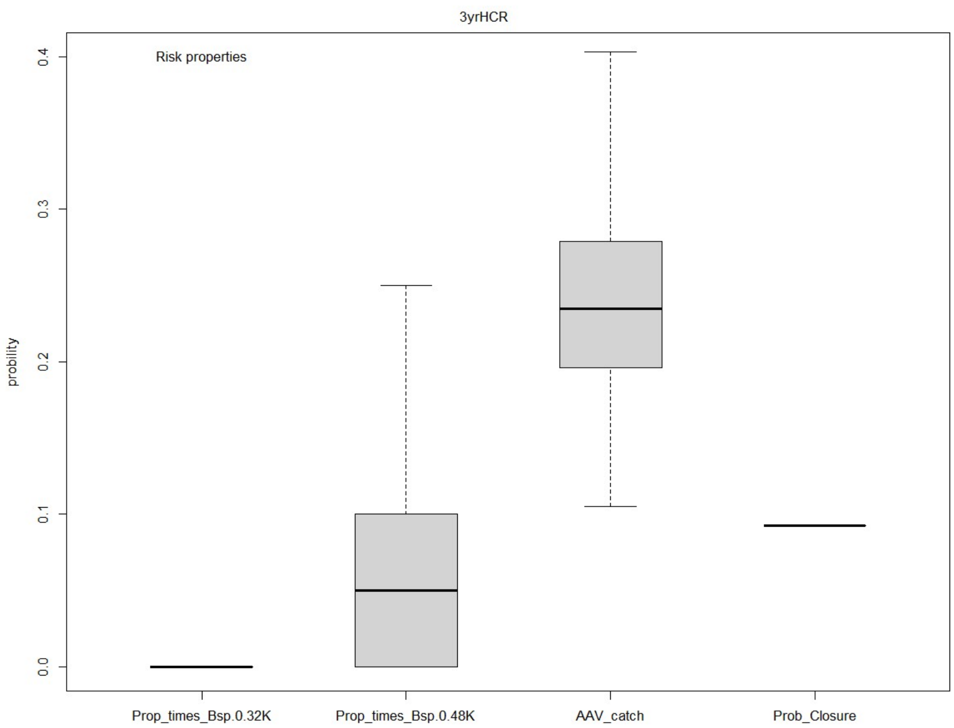



Fig. 6. Risk properties summary under eHCR 3yrHCR. Plots show the probability of depletion below each of two reference levels, $B_{LIM}$ = 0.32K and precautionary level 0.48K limit reference point, together the Average Annual Variability (AAV) of catch, and probability to close the fishery. The central line shows the median, the box the 75$^{th}$ and 25$^{th}$ percentiles and the whiskers represent the full range of projected values excluding outliers.

## DISCUSSION

A stock assessment model is usually used annually to analyse fishery data and assess current status and productivity of the resource as a basis for setting a RBC (Plagányi et al. 2014). The new approach involves using a formula for providing the RBC, based on pre-specified data inputs. The harvest control rule is empirical, as it uses the data directly e.g. recent upward or downward trends in abundance indices are used directly as feedback and hence the RBC changes in the same direction.

The eHCR for Australia's southern lobster is based on the catch-rate for the most recent year and hence reacts quickly to changes in catch-rates (Punt et al. 2012). To avoid high levels of inter-annual catch variability that can arise from such approaches, other lobster fisheries such as for the South African west coast lobster fishery (Johnston & Butterworth 2005) and Tristan da Cunha lobster fishery (Johnston & Butterworth 2013), base decisions on average catch-rates over a number of preceding years. Trying to track signals in the data rather than "noise" is similarly the motivation for the use of recent averages in the TRL eHCR. In addition, taking the natural logarithm was preferred because this has the effect of dampening some of the inter-annual variability and hence ensuring that the RBC responds to medium-term changes in resource trends rather than bouncing up or down more erratically due to potentially large inter-annual changes in observed CPUE.

The TRL stakeholders also expressed a preference to use a portfolio approach drawing on information from several data sources, including survey and CPUE data, albeit with more weight accorded to the most direct and accurate index, the 1yr survey index, compared with the pre-recruit 0yr index and the CPUE indices.

The eHCR has been extensively tested by simulation to provide appropriate trade-offs, taking into account a range of uncertainties and using methods that are now well established internationally (Dankel & Edwards 2016). The greatest advantages to adopt an eHCR approach are that (1) it can be applied quickly and easily to set a RBC in time for the start of the new fishing season; (2) it provides a transparent and easily understandable tool for stakeholders (e.g. the effect on the RBC of negative or positive decreases/increases in stock abundance indices can be readily seen, and a spreadsheet example is provided to stakeholders for this purpose); (3) it provides a sound basis for setting RBCs without compromising resource status; (4) it properly addresses concerns about scientific uncertainty through simulation testing to ensure that feedback secures reasonably robust performance across a range of plausible alternative resource dynamics; and (5) when tested using the MSE process, it empowers stakeholders by allowing them to transparently assess trade-offs between key performance measures and select the most favourable option taking into account a range of biological, economic, social and cultural considerations (Butterworth & Punt 1999, Butterworth 2007, Plaganyi et al. 2007, Rademeyer et al. 2007).

Harvest Control Rules are often complemented by "exceptional circumstances" clauses to account for unexpected events (Butterworth 2008) – for example, sizeable "walkouts" of South African west coast lobsters emerging onto beaches in response to low-oxygen events, greatly increasing the stock's mortality rate (Johnston & Butterworth 2005, Plaganyi et al. 2007). The TRL eHCR specifies that a stock assessment will be conducted every three years to rigorously assess stock status and productivity, and check that the eHCR is working as it is supposed to. As a stock assessment is only scheduled for every third year, action may not be taken quickly enough if the spawning biomass drops to very low levels, and hence an additional precaution has been built into the Harvest Strategy. Based on analysis of the historical pre-season and mid-year survey indices, a pre-season 1yr survey trigger point of 1.25 (average number of lobsters per survey transect and lower than any historically observed values) has been set, such that if this lower limit is triggered in any year, then the required action is that a stock assessment be conducted in the following year. This is similar to what is undertaken in some other fisheries, such as decision rules for some of the New Zealand substocks whereby a stock assessment is mandated if CPUE decreases below a specified base level (Bentley et al. 2005). If the stock assessment suggests that the spawning stock biomass is above the Limit Reference Point (LRP), then the process continues as previously. However, if spawning biomass is assessed as below the LRP, then a stock assessment is again triggered in the following year. If the second stock assessment suggests the stock is above the LRP, then the process again continues as previously, but if the spawning biomass is below LRP (i.e. two consecutive years with spawning biomass below LRP), then the fishery is closed and appropriate action (e.g. implementing surveys, analysing size structure and environmental information) is put in place. In general, the eHCR is therefore applied every year unless the LRP is triggered in two consecutive years. In response to the low stock abduance in 2018, the TRLRAG have discussed the possibility of increasing the empirical triger to be used to trigger action such as a stock assessment being conducted in a year. Ongoing work is exploring the implications of including additional survey information, as well as the possibility of some data not being available to inform the eHCR. This will usefully inform the settings for a tiered harvest strategy approach that accounts for the different risk-catch-cost trade-offs of different stock assessment and monitoring options (Dichmont et al. 2016). For example, if no data are available to inform on trends in the stock, then the RBC needs to be set at a lower level such as the 360t as previously recommended based on calibration to the same level of risk as the adaptive eHCR.

**APPENDIX – from Plaganyi et al. (2018)**

**METHODS**

The Torres Strait *P. ornatus* fishery is managed as a single stock and hence the assessment and management includes information from each of the three sectors: Australian TIB and TVH and the PNG sector which has a one-third share in the fishery. The stock comprises mainly three age classes, recently-settled (6 months old, termed 0yr), recruiting (average 1.5 years old, termed 1yr) and fished (average 2.5 years old, termed 2yr). The basic steps to evaluate the eHCRs are consistent with the best practice guidelines outlined by Punt et al. (2016).

The eHCR has been developed in close consultation with stakeholders at a number of meetings, including resource assessment groups (RAGs), fishery working groups and dedicated communication workshops.

**The Operating Model**

The stock assessment model of Plagányi et al. (2014) is used as the operating model OM and hence assumed to represent reality in terms of the underlying lobster population dynamics. The age-structured stock assessment model is a form of Statistical Catch-at-Age Analysis (SCAA) (e.g. Fournier and Archibald 1982) that fits to all available fishery-independent (surveys from 1989) and fishery-dependent data . The model was implemented using AD Model Builder which uses quasi-Newton automatic differentiation for statistical inference (Fournier et al. 2012).

Based on previous assessments, key uncertainties and sensitivities identified included choice of the stock-recruitment steepness parameter $h$, inclusion or not of an assumption of hyperstability for the two sectors (TIB, TVH) CPUE data, and alternative recruitment assumptions. No CPUE data were available for the PNG sector. A Beverton-Holt stock-recruitment relationship is used to estimate the number of recruits $R_y$ at the start of year $y$, allowing for annual fluctuation in the deterministic relationship:

$$R_y = \frac{\alpha B_{y-1}^{sp}}{\beta + B_{y-1}^{sp}} e^{(\gamma_y - (\sigma_R)^2/2)} \qquad (1)$$

where $B_y^{sp}$ is the spawning biomass at the start of year $y$, parameters $\alpha$, $\beta$ are based on the pre-exploitation equilibrium spawning biomass $K^{sp}$, and the "steepness", $h$, of the stock-recruitment relationship - $h$ represents the proportion of the virgin recruitment that is realized at a spawning biomass level of 20% of the virgin spawning biomass (Francis 1992):

$$\beta = \frac{\left(K^{sp}\right)\left(1-5h0.2\right)}{5h-1} \qquad (2)$$

and

$$\alpha = \frac{\beta + \left(K^{sp}\right)}{SPR_{virg}} \qquad (3)$$

where

$$SPR_{virg} = w_3^{st} N_3^{virg} \qquad (4)$$

with

$$N_1^{virg} = 1 \qquad (5)$$

$$N_a^{virg} = N_{a-1}^{virg} e^{-M_{a-1}} \qquad \text{for } 2 < a \le m \qquad (6)$$

where

$w_3^{st}$ is the mass of lobsters of age 3 (i.e. in December during the spawning season).

$m$ is the maximum age considered (taken to be 3).

Parameter $\gamma_y$ reflects fluctuations around the expected recruitment for year $y$, which is assumed to be normally distributed with standard deviation $\sigma_R$ (Appendix 1). The residuals are treated as estimable parameters in the model fitting process.

A hyperstable relationship was assumed between the CPUE relative abundance index for each sector $f$ and the exploitable biomass $B_y^{ex}$ as follows:

$$\left(\frac{\hat{C}}{E}\right)_y^f = q_f\left(B_y^{ex}\right)^{hyps^f} \quad (2)$$

where $hyps^f$, the hyperstability parameter per sector $f$ was set as described below. Pascoe et al. (2013) estimated a vessel level production function for the TIB and TVH fleet which included an estimate of the stock as one of the explanatory variables. From this, a hyperstability parameter estimate of around 0.5 was found for both fleets. For the TVH fleet, however, an interaction term between stock and fishing effort (dory days) was also significant, and increased this parameter value when both stock and effort was above the average level over the period 2004-2010. The study also found a strong economic incentive for the TVH vessels to increase their individual effort if less constrained. Given changes in restrictions on dory numbers and the improvement in stock size since this study was undertaken, it is expected that the relevant hyperstability parameter estimate for the TVH fleet would now be greater than 0.5. Hence, 0.75 was assumed in the stock assessment model, and a no-hyperstability sensitivity analysis is also included.

A Reference Set (RS) (Rademeyer et al. 2007) comprising four different Operating Models OMs (see Plaganyi et al. 2018) was constructed to include a sufficiently representative range of potential estimates of current population status and productivity. The choice of OMs was based on key uncertainties identified over the past few years during the annual stock assessment reviews that also included stakeholder inputs (Plagányi et al. 2012, Pascoe et al. 2013, Plagányi et al. 2014). These encompass uncertainty as to the stock-recruitment parameter $h$ and recruitment levels, as well as the hyperstability parameters as discussed above:

OM1: Based on stock assessment model with $h=0.7$; and hyperstability (*hyps*) parameters for CPUE TVH and TIB sectors set at $hyps1 = 0.75$ and $hyps2 = 0.5$ respectively;

OM2: More conservative steepness parameter $h=0.5$ of the stock-recruitment function (and with $hyps1=0.75$; $hyps2=0.5$);

OM3: No hyperstability assumed (linear index) i.e. $hyps1=1$; $hyps2 = 1$ (and with $h=0.7$);

OM4: As in OM1 but testing sensitivity to more negative recruitment scenarios with possible autocorrelation. This is implemented by randomly (10% probability of this occurring in any year) forcing recruitment to be three-quarters of the level from Equation (1) in that particular year (Recruitment(year2)), and generating a random autocorrelation parameter $\rho$, where $\rho$ determines the extent to which the recruitment in the second year is similar to that in the previous year, i.e.

Recruitment (year 2)* = $\rho$ x Recruitment(year1)+$(1-\rho)$ x Recruitment(year2).

Each of the four OMs is fitted over the historical period 1973 – 2015, and the model then used to do 20-year forward projections. All model results are integrated across these four alternative models, with equal weight accorded to each, and 200 replicates of each OM, yielding a total of 800 projection scenarios over which results are integrated. The OMs are all assumed to be plausible alternative representations of the system and to reflect key uncertainties, hence they are accorded the same weight rather than AIC-weighting for example, in line with recommendations by Punt et al. (2016). Best practice guidelines are also followed in dividing the trials into 'reference' and 'robustness' sets (Rademeyer et al. 2007, Punt et al. 2016) as described further below.

### Future Projections

"Future data" in the form of survey indices of abundance (Pre-season 0yr, 1yr) and sector-specific CPUE series (TIB and TVH) are required by the eHCR to compute a RBC for each of the years in the projection period for each candidate rule tested. These abundance indices (CPUE and surveys) are generated from the OM, assuming the same error structures as in the past (see Appendix). For the CPUE data, additional sources of variation were accounted for by increasing the standard deviation estimates to 0.4. This is also because when computing the RBC for year $y$+1, CPUE data are assumed to be available for year $y$, but as these indices are based on all data available at the end of October, there may be an additional error if there is a delay in some of the data being submitted and analysed in time for that year's analyses. The future CPUE data series are generated from model estimates for exploitable biomass and catchability coefficients.

Future survey data are generated from model estimates of pre-season (November) survey biomass. Log-normal error variance includes the survey sampling variance with the standard deviation set equal to the average historical values of 0.18 and 0.35 respectively for the 1yr and 0yr indices. For the RBC for year $y$+1, such data are available for year $y$.

### Simulating RBCs and actual catches

The total RBC is divided in fixed proportions $p_f$ amongst the various sectors $f$, with the following values used for the sector allocations: TIB: 38%, TVH: 29%, PNG: 33%. We include in this model implementation uncertainty which is defined as the difference between the model RBC and the actual catch that is taken in a year. Sources of implementation uncertainty can include unreported catches, discarded catches or lower than expected catches due to capacity constraints and socio-cultural drivers (Van Putten et al. 2013). It was considered important to include implementation uncertainty for a number of reasons: (a) observed substantial differences between the actual catches and the nominal TAC over the past decade (during which time a proposed move to output controls has been trialed), as well as in the performance of the three sectors relative to their nominal allocation (the RBC was not strictly binding as the system was under an input control system); (b) challenges in ensuring that under a quota management system each of the three sectors (TIB, TVH, PNG) will effectively monitor catches during the fishing season and ensure that fishing stops when the limit is reached; (c) uncertainty as to possible discard mortalities under quota management, which may be exacerbated during anomalously warm periods due to higher associated mortality rates of captured lobsters: the fishery is predominantly for live animals that are held in relatively high densities in sea cages that may suffer from reduced water circulation, are close to the surface and as such, may be vulnerable to overheating or reduced oxygen during periods of low water movement and high temperatures); (d) whether decision makers accept or change the scientifically-based RBC recommendation (no precedent for this scenario); (e) potential (unknown) catches of TRL from other sources; and (f) unknown future changes in fishing operations.

The relationship between the RBC for year $y$ ($RBC_y$) and the actual catch in year $y$ ($C_y$), given proportional allocations $p_f$ per sector, is modelled using the formula:

$$C_y = \sum_{f=1}^{3} p_f RBC_y \times e^{\varepsilon_y^f} \;,\; \varepsilon_y^f \; from \; N(0;\sigma_f^{\,2}) \qquad (7)$$

where catch is the total from the three sectors and a value for $\sigma_f$ for each sector was selected based on comparison with past observations over the period 2006-2015. Different implementation error magnitudes are set using $\sigma_{TIB}$ (0.06), $\sigma_{TVH}$ (0.04) and $\sigma_{PNG}$ (0.1). These values can be adjusted, for example, to simulate scenarios in which different sectors reduce the difference between total catch and the allocated catch based on the RBC. Sensitivity to alternative values of $\sigma_f$ was also investigated.

**Candidate eHCRs considered**

We focused on empirical approaches for the reasons elaborated above. Hence, the HCRs tested were "model-free" (sensu Rademeyer et al. 2007), increasing or decreasing the RBC in response to the magnitude of recent trends in CPUE and survey estimates.

A range of alternatives were tested that included different combinations of all available indices of abundance, including options that accorded zero weight to some abundance series (Table 1). Four different kinds of HCRs were tested as follows:

(1) Constant Catch – a range of alternative values, including a fixed average, were tested and are briefly discussed given some stakeholders expressed a preference for using a fixed annual catch.
(2) Slope - Based on a simple fixed slope parameter applied to the pre-season survey indices – this option is not described further as it performed poorly relative to the options below.
(3) Regression – Based on the slope of a regression line that is fitted each year to the past *n* (*n*=5 was the preferred choice following testing using *n*=3 and *n*=6) survey data points, and similarly for CPUE where included, and multiplied by either a fixed average historical catch or a moving average of the previous 5 year's catch.
(4) Log Regression – As above, except that the slope is computed based on the natural logarithm of the survey and CPUE indices in an attempt to decrease inter-annual variability.

In all these cases, an additional option was included to cap the maximum catch (1000 t in base-case). The basic form of the HCR rule for Options (3) and (4) uses the pre-season survey 1yr and 0yr indices, both sector CPUE indices, with or without natural logarithms of the slopes, an upper catch limit, and using weightings as shown in Table 1 was as follows:

$$\begin{aligned} TAC_{y+1} &= wt\_s1 \cdot \left(1+s_y^{presurv,1}\right) \cdot \bar{C}_{y-4,y} + wt\_s2 \cdot \left(1+s_y^{presurv,0}\right) \cdot \bar{C}_{y-4,y} \\ &+ wt\_c1 \cdot \left(1+s_y^{CPUE,TVH}\right) \cdot \bar{C}_{y-4,y} + wt\_c2 \cdot \left(1+s_y^{CPUE,TIB}\right) \cdot \bar{C}_{y-4,y} \end{aligned} \quad (8)$$

or if $TAC_{y+1}$ > 1000t, $TAC_{y+1}$ = 1000.

where

$\bar{C}_{y-4,y}$ is the average achieved catch during the past 5 years, including the current year i.e. from year *y*-4 to year *y*,

$s_y^{presurv,1}$ is the slope of the (logarithms of the) pre-season survey 1yr abundance index, based on the 5 most recent values;

$s_y^{presurv,0}$ is the slope of the (logarithms of the) pre-season survey 0yr abundance index, based on the 5 most recent values;

$s_y^{CPUE,TVH}, s_y^{CPUE,TIB}$ is the slope of the (logarithms of the) TVH and TIB CPUE abundance index, based on the 5 most recent values;

wt_s1, wt_s2, wt_c1, wt_c2 are tuning parameters that assign relative weight to the pre-season 1yr (wt_s1) and 0yr (wt_s2) survey trends compared with the CPUE TVH (wt_c1) and

TIB (wt_c2) trends, with some key alternatives considered as summarized in Table 1. A "hockey-stick" rule (eHCR11) was also tested (Table 1), with the example shown applying eHCR1 whenever the 1yr survey index was above the threshold value of 1.25, but with RBC set to zero if the 1yr survey index fell below limit reference level of 0.8, and the RBC set as a linearly decreasing proportion of the value computed using eHCR1 for survey values between the limit and threshold values.

**Management Objectives**

The management objectives identified for the TRL fishery are as follows:

- maintain the stock at (on average), or return to, a target biomass point $B_{TARG}$ equal to recent levels (2005-2015) that take account of the fact that the resource is shared and important for the traditional way of life and livelihood of traditional inhabitants and is at a level which is biologically and economically acceptable;
- maintain stocks above the limit biomass level ($B_{LIM}$), or an appropriate proxy (selected as half the $B_{TARG}$ level), at least 90 per cent of the time;
- Implement rebuilding strategies, if the spawning stock biomass is assessed to fall below $B_{LIM}$ in two successive years.

Candidate HCRs are evaluated as to their ability to maintain the resource as fluctuating about the target level and to ensure that they do not pose unacceptable risk to the spawning biomass. Quantifying the risk to the resource under alternative HCRs assists in the final selection of a HCR which meets the objectives of low risk of depleting the spawning biomass as well as ensuring that potential economic gains are not lost due to an overly conservative approach. Projected future catch rates for the TVH and TIB sectors are used as a proxy for economic performance, and an additional consideration relates to the inter-annual variability in catch. Stakeholders also expressed a preference for an upper limit to be set on the total annual catch to reduce biological risk.

**Performance Statistics**

Projections were conducted over 20 years and 200 replicates of each of the four OMs, i.e. a total of 800 simulations. The same set of random numbers were used in testing all HCR candidates. In each case the median and 75$^{th}$ and 25$^{th}$ percentiles of all key outputs were computed, and the range of values also shown for the full projection period given that there is a lot of inter-annual variability in stock biomass. Examples of individual trajectories (worm plots) are also presented. These are randomly drawn individual catch, spawning biomass and CPUE trajectories, which are examples of plausible future outcomes, noting that the median projections shown are not representative of any individual plausible outcome. The following performance statistics, were computed for each candidate harvest control rule (HCR):

- $B^{sp}_{2034} / B^{sp}_{1973}$ the expected median spawning biomass at the end of the projection period, and for all year *y*, relative to the starting (1973) level (used as a proxy for carrying capacity *K*).
- $B^{sp}_{2034} / B^{sp}_{unfished}$ the expected median spawning biomass at the end of the projection period, and for all year *y*, relative to the comparable no-fishing level (i.e. biomass at the end of the 20-year projection period when assuming zero future fishing, yielding a dynamic rather than equilibrium reference point as is considered more suitable for highly variable stocks).
- Risk of depletion: number of times in 20-year forward projection that biomass decreased below a reference point, expressed as proportion (e.g. 1/20=0.05) of all individual runs with projected biomass below (a) the Limit Reference Point (LRP) where $B_{LIM}$ = 0.32K and (b) below precautionary level 0.48K.

- Average catch: $\overline{C} = \frac{1}{20}\sum C_y$ over 2015 to 2034
- Average Annual Variability (AAV) of Catch $\frac{1}{20}\sum \frac{|C_y - C_{y-1}|}{C_{y-1}}$
- Projected future CPUE for comparison with historical observations for the TVH (1994-2013) and TIB (2004-2013) sectors
- Projected average fishing mortality

**Tuning and designing HCR with stakeholder input**

A large number of alternative HCRs were trialled and the resultant trade-offs presented to stakeholders to select a preferred HCR (e.g. trade-off to ensure high average annual catch but low risk of depletion of lobster population). Tuning parameters included: weighting of pre-season data vs TIB CPUE, TVH CPUE; number of years to compute slope over as applied to trends in abundance indices, catch multipliers in the decision rule, the form of slope regression (e.g. using logarithm of indices). Alternatives were also investigated to impose constraints on the extent the RBC can vary, or setting the maximum and minimum values. The results from testing a wide range of alternative candidate HCRs are not repeated here and instead this paper focuses on the final subset (see Table 1) used to obtain consensus from stakeholders on choice of the final eHCR.

**Robustness tests**

As recommended by Cooke (1999) and Rademeyer et al. (2007), the RS reflects the current best representation of the resource dynamics and associated uncertainties, but a further broader set of robustness tests is also considered to further ensure that the final choice of eHCR is robust to a full range of uncertainties. As the TRL fishery has never been closed and has been maintained at a relatively high average biomass level, it is important to minimize the risk of fishery closure given this would have large socio-economic impacts. The final set of HCRs were thus subjected to a number of sensitivity and robustness tests to see how well they would perform under more severe conditions, and the risk of closure was used as a key statistic to distinguish the performance of alternative candidate HCRs. The following final robustness tests are presented here (Table 2):

(a) higher implementation error, particularly for PNG given unexpectedly large trawling catches were reported in 2014 (Sens1);

(b) several scenarios with increases or decreases in future catchability, such as might arise due to changes in fishing efficiency under quota management, or environmental influences such as sand incursions changing the distribution and availability of lobsters, but not necessarily total abundance (Sens2-4);

(c) several negative recruitment scenarios to see how well the eHCR might perform if there are unexpected low recruitment events in the future, such as due to environmental influences (Sens5-8);

(d) periodic large increases in natural mortality rates of the lobsters, such as could occur in anomalously warm years, as has been the actual case recently (Sens9).

(e) an increasing trend in the future mortality rate of large 2yr lobsters due to environmental impacts associated with climate change (Sens10).

In addition, the robustness tests above were repeated using a constant catch scenario, with annual catch equal to 680t (average of last 10 years), as this option was preferred by some stakeholders. A final scenario was calibrated to have the same overall risk to the resource and fishery as eHCR7, but with a fixed annual catch.

## RESULTS

For each HCR, there are a large number of performance statistics output for consideration by stakeholders. For all statistics, values shown are the median of the 800 replicates, together with the 75$^{th}$ and 25$^{th}$ percentiles (i.e. the rectangles encompass 50% of all outcomes for box and whisker plots) as well as the range of values excluding outliers (Fig. A.1).
The constant catch option (eHCR12) had a much higher risk of the stock falling below the limit biomass reference level of 32% of *K* (Fig. A.1) than any of the adaptive options. Preliminary testing ruled in favour of basing the HCR on an average of the last five years' data in preference to three or six years (for indices of abundance) or a fixed average catch (Plagányi et al. 2016). Preliminary testing also found relatively poor performance in terms of the risk-catch trade-off if only fishery-dependent CPUE data were used, compared with HCRs including survey data catch (Plagányi et al. 2016).
There were several examples of HCRs (e.g. eHCR1, eHCR5, eHCR6) that yielded high average catch for low risk across a range of alternative weightings accorded to the survey and CPUE information (Table A.1, Fig. A.1). Stakeholders preferred the HCR candidates that used the log of the slope because it reduced catch variability compared with candidates not based on the log of the slope, such as eHCR2 and eHCR4 in Fig. A.1. The candidate eHCR11 that used a hockey-stick type rule to adjust catches was also considered to result in overly variable catches corresponding to a relatively poor median catch (Fig. A.1).

The TRLRAG reviewed the performance of a range of HCRs, and gradually reduced the set for final consideration based on considerations such as yielding an average catch that was too low compared to other strategies for the same overall risk (e.g. eHCR10), strategies that were too risky in terms of risk of depletion of the resource or risk of closure of the fishery (e.g. eHCR12), as well as being too variable (e.g. eHCR11).

The final set of HCRs performed similarly, specifically eHCR1, eHCR5 and eHCR6. The TRLRAG discussed the relative advantages and disadvantages of according more or less weight to the four different abundance indices, acknowledging that the pre-season 1yr index provided the most reliable and most direct indication of how many lobsters would be available to be fished the following year. On the other hand, it was noted that these data are derived from a survey that is conducted only once a year, whereas the CPUE data indexes the overall abundance throughout the fishing year, and by both sectors. The CPUE index provides a measure of the spawning biomass, rather than next year's fishable biomass, but including it in the HCR means that the rule will take account of likely future changes in recruitment, and hence enable proactive adjustments in the setting of RBC's. Similarly, the pre-season 0yr index is equivalent to the 'puerulus index' used in several lobster fisheries, and similarly provides an early heads up of likely future stock levels. Several stakeholders felt that it would be advantageous to include a portfolio of abundance indices (both to spread the risk and utilise all available information) in the final HCR. The final HCR selected by the TRLRAG eHCR7 accords equal weights of 10% to each of the two CPUE series, as well as pre-season 0yr index, and a larger weight of 70% to the pre-season 1yr index.

In addition, several stakeholders felt that it was important to include an upper limit for the RBC. The possibility of using limits such as 800 tonnes was considered, but it was shown that this may be unnecessarily low and may lead to the average catch declining over time, and testing showed that an upper limit of 1000t avoided these problems.

The final selected eHCR rule is as follows, and uses the pre-season survey 1yr and 0yr indices, both CPUE indices, taking natural logarithms of the slopes, an upper catch limit, and using weightings as follows:

$$RBC_{y+1} = \left[0.7 \cdot \left(1 + s_y^{presurv,1}\right) + 0.1 \cdot \left[\left(1 + s_y^{presurv,0}\right) + \left(1 + s_y^{CPUE,TVH}\right) + \left(1 + s_y^{CPUE,TIB}\right)\right]\right] \cdot \bar{C}_{y-4,y}$$

$$\text{or if } RBC_{y+1} > 1000\text{t}, \; RBC_{y+1} = 1000. \qquad (9)$$

The performance of the final eHCR in terms of two key measures, namely projected spawning biomass and total catch, is illustrated in Fig. A.2. The plot shows the distribution of potential future outcomes relative to the historical observed catches and spawning biomass as estimated by the stock assessment model. Projected medians and associated ranges remained close to target levels for spawning biomass relative to the starting (1973) level, as well as relative to the comparable no-fishing level, and projected fishing mortality (after applying implementation errors) fluctuated around the target level.

Focusing on median values can give a false idea of the extent of inter-annual variability that may be observed in future catch and CPUE because the median does not represent an actual trajectory. Hence examples of individual worm plots (Fig. A.3) were also presented to stakeholders.

Under the final set of sensitivity tests (Table A.2), the median risk of depletion associated with the eHCR remained at or below the reference level of 10% and the catch variability increased by a maximum of 50% (Fig. A.4), suggesting the eHCR will perform satisfactorily even if there are unexpected and unusual situations that arise in the future. The model suggested a moderate increase in risk under a scenario with a large sustained increase in catchability (Sens2; Fig. A.4) that remains undetected over time, which means a model will most likely overestimate resource biomass and as a consequence catches and fishing mortality will be too high.

As this fishery is largely recruit driven, changes in recruitment can be expected to have a large impact on the stock and fishable biomass. The poor recruitment sensitivities (Table A.2 and Fig. A.4) result in a slight decline in average spawning biomass over time, and an increase in the risk of depletion (although not >10%), but the eHCR brings catches down in response, so as to reduce risk to the resource. Similarly, if there are occasional increases in natural mortality rate, catches are decreased and the overall risk to the resource remains low. If there is a sustained increase in the mortality of the large lobsters (Sens10), this results in a drop in the average spawning biomass and increase in the risk of depletion below the LRP as well as an increased risk of closure of the fishery (Fig. A.4), even given the decline in catches. However the risk to the resource is acceptable (median risk of biomass dropping below the LRP <=10%) even under this extreme scenario, which provides support as to the robustness of the eHCR.

Figure A.5 compares the performance of the final eHCR and a constant catch scenario (680t) under the last five of the above sensitivity tests. The constant catch scenario consistently results in higher risk to the resource (Fig. A.5) and the risk of closure is approximately doubled.

## ACKNOWLEDGEMENTS

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Table A.1. Summary of eHCR final set of candidates, showing range of alternative weightings used in testing candidate eHCRs assigning different weighting to the four available indices of abundance, and ranging from using the key survey 1yr index only through to using only fishery-dependent CPUE data. Results are shown for the subset labelled revised HCR.

| **Candidate HCR Name** | **Description with Ln(slopes last 5yrs) unless indicated** | **Indicator (all Catch_ave_5yrs unless indicated)** | | | |
|---|---|---|---|---|---|
| | | **Pre1** | **Pre0** | **CPUE_TVH** | **CPUE_TIB** |
| Primary indicator only | Weighting on single indicator (Pre1) | 1 | 0 | 0 | 0 |
| Fishery-dependent only | Equal weighting of fleet indicators only | 0 | 0 | 0.5 | 0.5 |
| **Revised HCR** | | | | | |
| eHCR1 | Weighting factor on all indicators | 0.6 | 0.1 | 0.15 | 0.15 |
| eHCR2[1] | Weighting factor on all indicators | 0.6 | 0.1 | 0.15 | 0.15 |
| eHCR3 | Weighting factor on all indicators | 0.6 | 0.3 | 0.05 | 0.05 |
| eHCR4[1] | Weighting factor on all indicators | 0.6 | 0.3 | 0.05 | 0.05 |
| eHCR5 | Weighting factor on all indicators | 0.8 | 0.1 | 0.05 | 0.05 |
| eHCR6 | Weighting factor on all indicators | 0.7 | 0.2 | 0.05 | 0.05 |
| eHCR7 | Weighting factor on all indicators | 0.7 | 0.1 | 0.1 | 0.1 |
| eHCR8 | Weighting factor on all indicators | 0.5 | 0.1 | 0.2 | 0.2 |
| eHCR9[2] | Weighting factor on all indicators | 0.41 | 0.21 | 0.19 | 0.19 |
| eHCR10[3] | Weighting factor on all indicators | 0.6 | 0.1 | 0.15 | 0.15 |
| eHCR11[4] | Weighting factor on all indicators | 0.6 | 0.1 | 0.15 | 0.15 |
| eHCR12 | Constant Catch 700 | | | | |

**Notes**

[1]*No log of slope - variability higher*

[2]*Inverse of sigma*

[3]*Catch_ave=665t*

[4]*Hockey Rule; Surv_lim=0.8; Surv_trig=1.25*

Table A.2. Summary of robustness tests.

| Sensitivity Test | Description | Details |
|---|---|---|
| Sens1 | Higher implementation error | PNG Implementation error = 0.3 |
| Sens2 | Sustained increase in catchability & Sens1 | Catchability *q* is 1.2**q* for all future years |
| Sens3 | Catchability decrease | 20% prob that catchability is 0.6*q* in any 1 year eg sand incursion |
| Sens4 | Catchability increase & Survey Obs error | 20% prob that catchability is 1.3*q* in any 1 year & variance doubled for Preseason survey |
| Sens5 | Poor recruitment periodically | 20% prob that recruitment halved compared to expected level |
| Sens6 | Less frequent very poor recruitment event | 10% prob that recruitment one-third compared to expected level |
| Sens7 | Less frequent poor recruitment | 10% prob that recruitment half compared to expected level |
| Sens8 | Less frequent poor recruitment & inc M | 10% prob that recruitment half compared to expected level & Mortality M increase 20% |
| Sens9 | Infrequent large increase in mortality | 10% probability that mortality M increases by 50% in any one year |
| Sens10 | Increase in mortality of spawning lobsters | One-third increase in future mortality rate of 2+ lobsters |

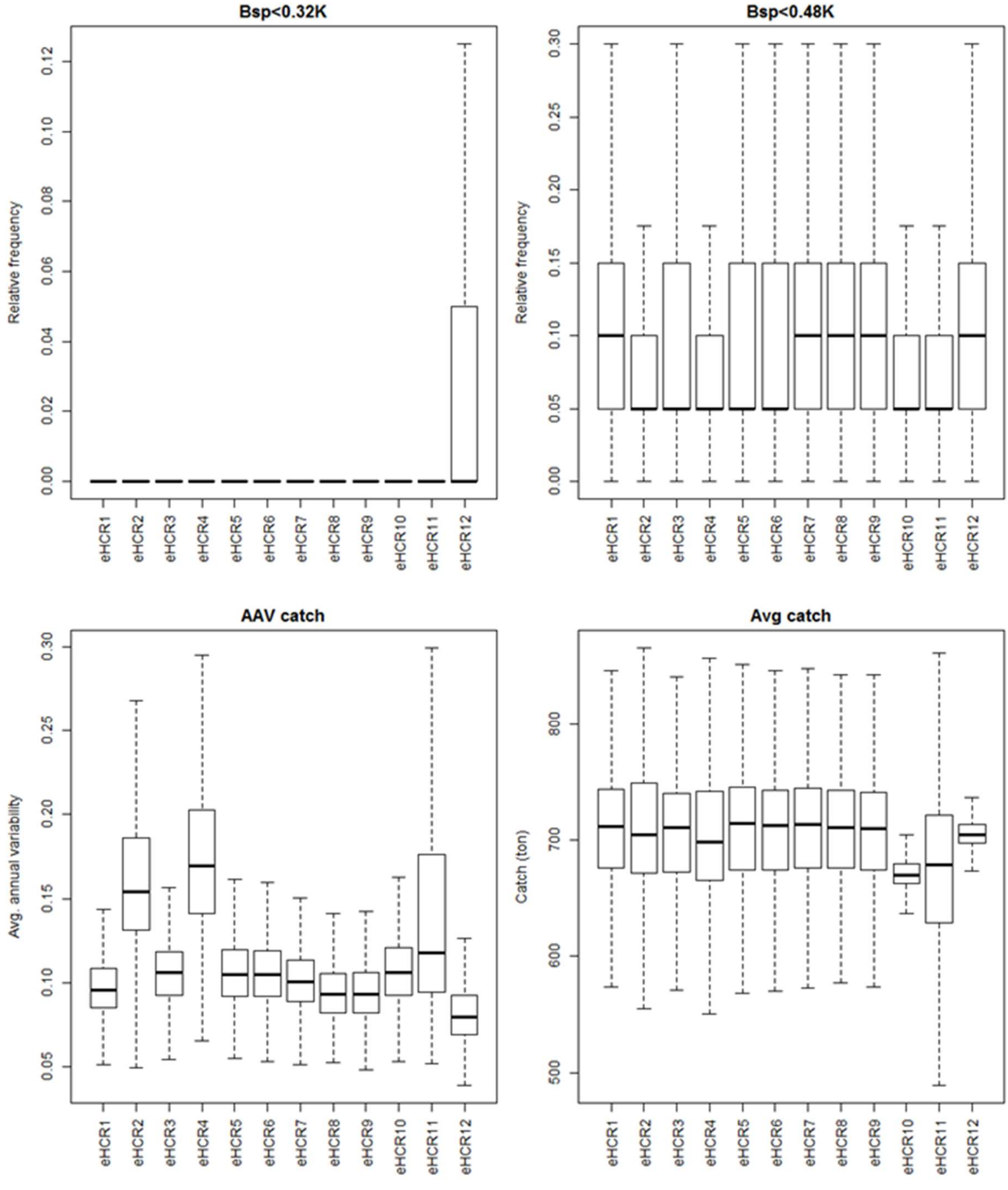


**Figure A.1.** Comparison of some key performance statistics for final set of eHCRs. Plots show the probability of depletion below each of two reference levels, $B_{LIM}$ = 0.32K and precautionary level 0.48K limit reference point, together the Average Annual Variability (AAV) of catch, and total annual catch (t). The central line shows the median, the box the 75th and 25th percentiles and the whiskers represent the full range of projected values excluding outliers.

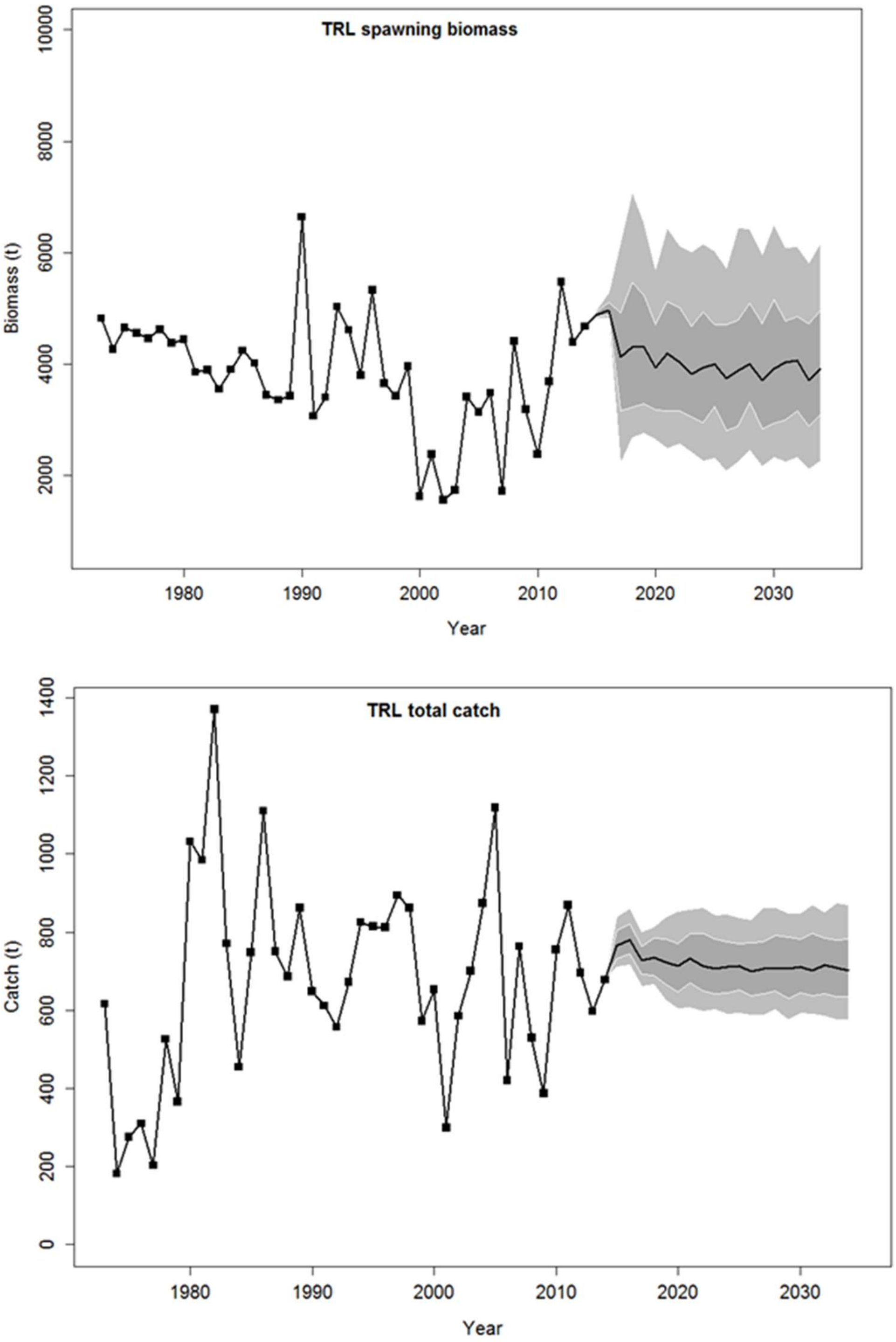


**Figure A.2.** Distributions (solid line: median, 50% intervals: dark shaded area, 80% intervals: light shaded area) of future projected (A) spawning biomass, and (B) total catch (t) for TRL compared with historic values and when using the final eHCR (eHCR7).

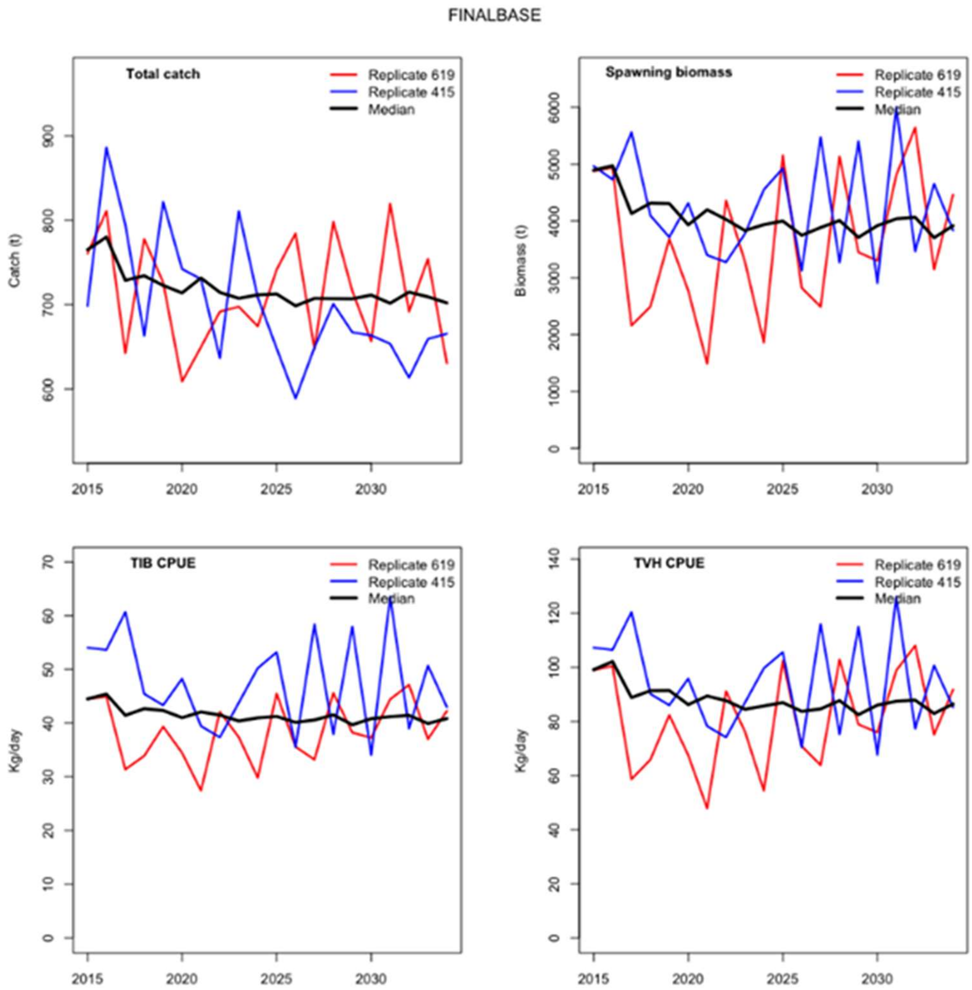


**Figure A.3.** Worm plots showing two randomly selected individual trajectories compared with the median values of total catch and spawning biomass (top panels) and projected CPUE for the two sectors TIB and TVH (bottom panel).

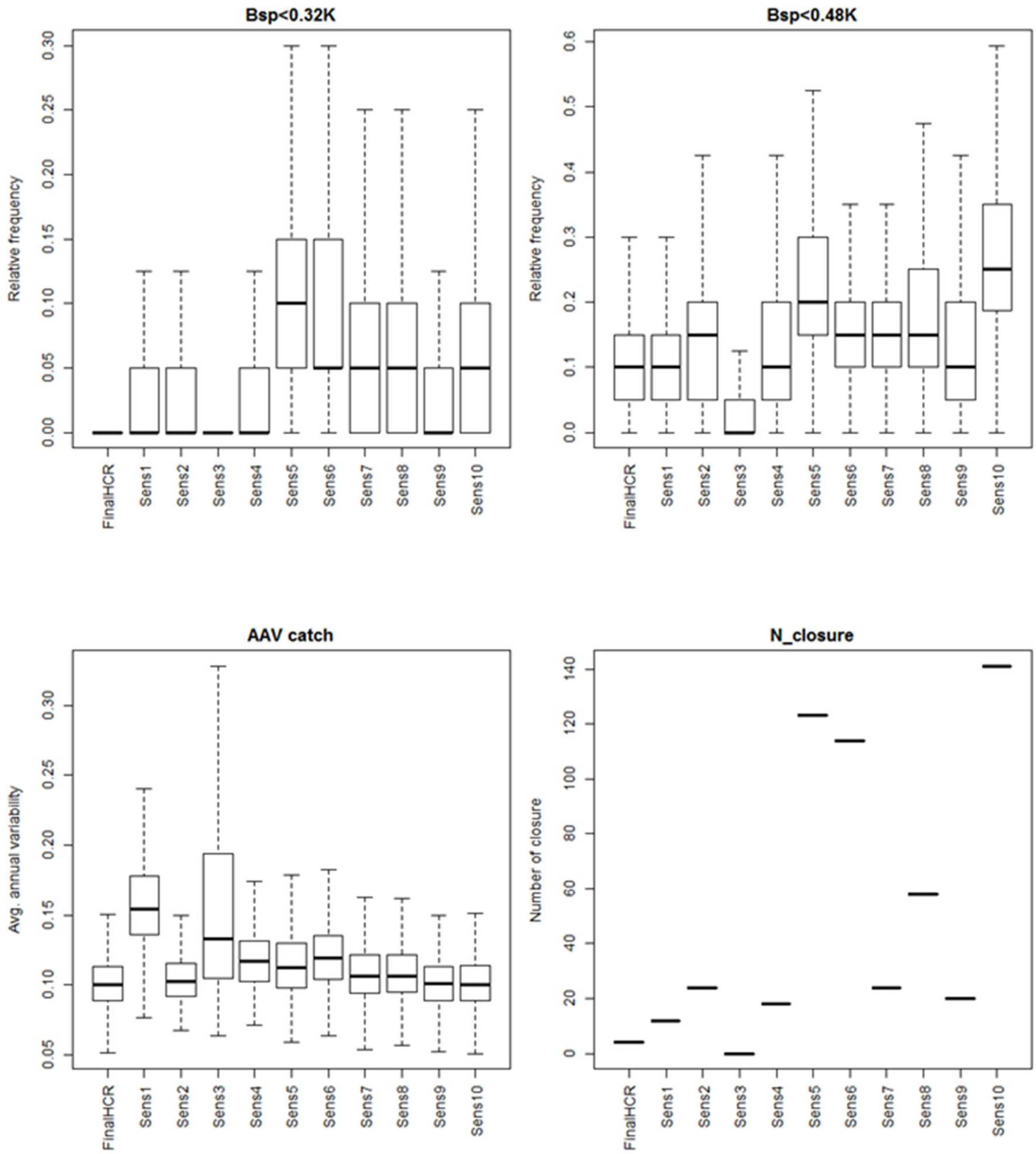


**Figure A.4**. Selected performance statistics for final set of sensitivity tests. Plots show the probability of depletion below each of two reference levels, $B_{LIM}$ = 0.32K and precautionary level 0.48K limit reference point, together the Average Annual Variability (AAV) of catch, and relative number of fishery closures triggered in the simulations. The central line shows the median, the box the 75th and 25th percentiles and the whiskers represent the full range of projected values excluding outliers.

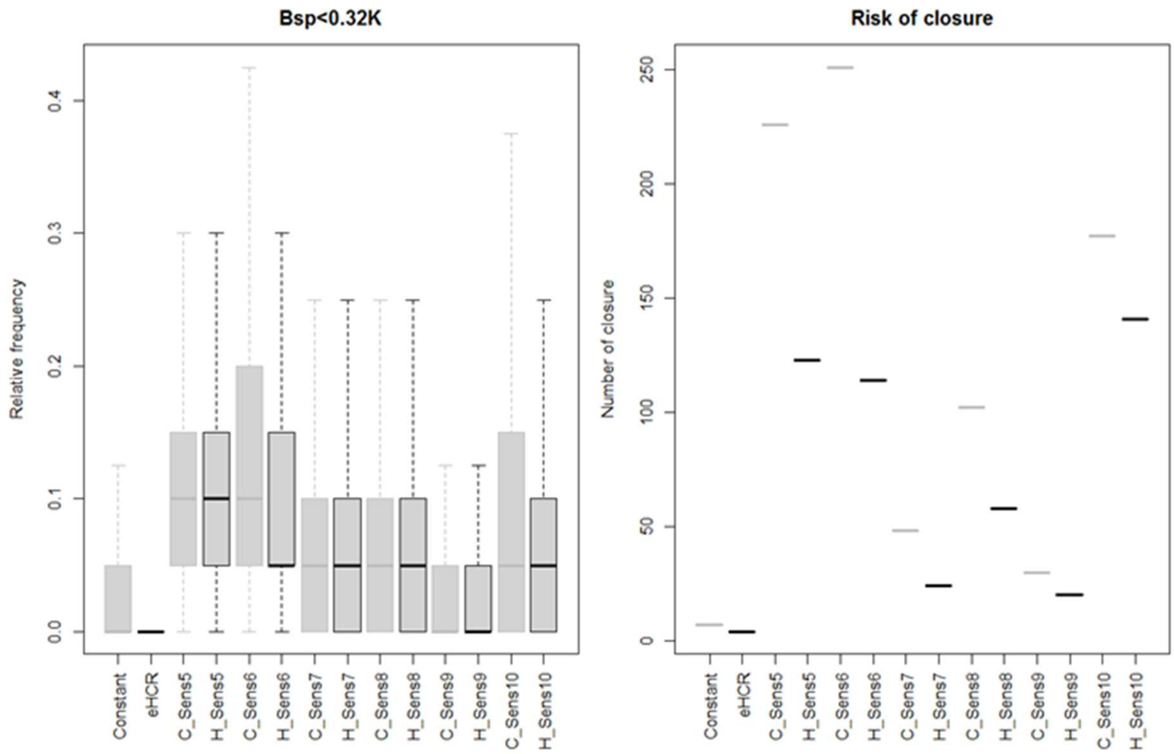


**Figure A.5.** Comparison between final eHCR (H) and constant catch (C) set at 680t performance statistics using final set of robustness tests Sens5 to Sens10, and showing performance in terms of risk of dropping below the limit reference point (0.32K) and relative risk of a fishery closure (from 800 simulations). The central line shows the median, the box the 75th and 25th percentiles and the whiskers represent the full range of projected values excluding outliers.

| | |
|---|---|
| **TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG)** | **MEETING 25**<br>**11-12 December 2018** |
| **OTHER BUSINESS** | **Agenda Item 6**<br>**For Discussion** |

**RECOMMENDATIONS**

1. That the RAG **NOMINATE** any further business for discussion.

| TROPICAL ROCK LOBSTER RESOURCE ASSESSMENT GROUP (TRLRAG) | MEETING 25<br>11-12 December 2018 |
|---|---|
| DATE AND VENUE FOR NEXT MEETING | Agenda Item 7<br>For Decision |

**RECOMMENDATIONS**

1. That the RAG **NOMINATE** a date and a venue for the next meeting.

**BACKGROUND**

2. The next meeting is proposed for February 2018 on Thursday Island. An indicative timeline for determining the final total allowable catch for the 2018/19 fishing season is provided at **Attachment 7a** for reference.

**Indicative timeline for determining the final total allowable catch for the 2018/19 fishing season**

| Steps | Description | Timeline |
|---|---|---|
| Pre-season scientific survey | Results are used to update the annual stock assessment. Survey must be conducted in November to provide comparable results overtime and the most accurate estimate of annual lobster recruitment into the fishery. | November 2018 |
| Stock assessment update | Conducted by CSIRO with preliminary stock assessment results within 4-5 weeks of the pre-season scientific survey. | early December 2018 |
| TRLRAG advice | Review the preliminary stock assessment results and Recommended Biological Catch (RBC) advice. Provide advice on finalising the assessment and RBC advice.<br>Officers from PNG National Fisheries Authority (NFA) invited to attend all PZJA advisory forums and are scheduled to attend the TRLRAG meeting on 11-12 December. | 11-12 December 2018 |
| | Consider final stock assessment and recommend final RBC. | Early February 2019 |
| TRLWG advice | Consider TRLRAG advice on the RBC and recommend a final global TAC. | Early February 2019 |
| Treaty obligations | AFMA CEO and PNG NFA Director General to meet regularly to discuss PZJA forum deliberations and cross-endorsement and catch sharing arrangements under the Treaty.<br>Australia and PNG Fisheries Bilateral Meeting. Agree on final global TAC, cross-endorsement and catch sharing arrangements under the Treaty. | Bilateral meeting due to be scheduled for February 2019 |
| PZJA or Delegate | Agree final 2018/19 TAC for the TRL Fishery (i.e. Australia's catch share of the final global TAC). | End of February 2019 |