# Sustaining productivity of tropical red snappers using new monitoring and reference points

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Project No. 2009/037

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## 1 NON TECHNICAL SUMMARY

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**OBJECTIVES:**

1. Analyse current monitoring and logbook data sets, as well as survey and other information, to establish whether these data provide sufficient power to develop critical indicators of fishery performance.
2. Provide a risk analysis that examines the use of age structure and catch rate information for development of critical indicators, and response rules for those criteria, in the absence of other fishery information.
3. Develop a monitoring program that uses commercial vessels from the fishery to provide independent data.

**NON TECHNICAL SUMMARY:**

**OUTCOMES ACHIEVED TO DATE**

The project outputs have contributed to or will lead to the following outcomes:

1. Improved monitoring, management and sustainable use of tropical snapper resources. The outputs will contribute to long term profitability and marketability of the fisheries, plus reduce management costs.
2. Detailed monitoring specifications to implement a Northern Australian harvest strategy for tropical snappers. The outputs defined the discrete components and spatial scale at which management should operate. The project outputs, together with a future monitoring and harvest strategy, will provide greater business certainty for industry through establishing an open and transparent process to manage the fisheries.
3. Promoted a multi-jurisdictional management framework and enhanced multi-agency research collaborations for fishery assessments. The project provided evidence for a combined monitoring/assessment/management approach for shared fish stocks across Northern Australia. The project highlighted the need to share financial resources in order to effectively monitor and manage long-lived tropical snappers. The project better informed stakeholders and managers about their jurisdictional and sectoral linkages.
4. The project delivered on the Northern Australian Fisheries Committee (NAFC) priority for tropical snapper research.
5. The project examined monitoring options for golden snapper that will support other Northern

Territory research on this species.

6. The data and modelling outcomes from this project will be relevant to and support the ACIAR project FIS/2006/142 "Developing new assessment and policy frameworks for Indonesia's marine fisheries, including the control and management of illegal, unregulated and unreported (IUU) fishing".

7. Project results were communicated through a number of meetings with Queensland and Northern Territory fish trawl operators, and fishery managers. Fisheries Queensland and NT fishery managers have actioned discussions and planning for a four year monitoring cycle. Operators agreed in concept to gather the necessary data to make assessments more robust. It was considered desirable to match the four-year monitoring cycle between the jurisdictions; preferably starting 2012.

8. Project results contributed to Goldband snapper stock assessments conducted by NT government and Dr Carl Walters in July 2011.

Australia's tropical snapper fisheries harvest six main Lutjanid species. They are the Crimson, Saddletail, and Goldband snappers, Red Emperor, Golden snapper and Mangrove Jack. These fish live up to 40 years of age, weigh up to five to ten kilograms and are highly valued for commercial marketing. The fisheries operate in tropical offshore waters across northern Australia from the Kimberley coast to the Gulf of Carpentaria. The fisheries are primarily commercial using demersal trawl, trap and line fishing gear. The fisheries have a long and varied history of foreign and domestic exploitation. Indicative foreign harvests were two to five kilotonnes per year up to 1990. After 1990, foreign vessel permits were removed and domestic fishing expanded landing in the order of two to three kilotonnes of tropical snappers annually.

In 2007, NAFC listed tropical snapper research as a priority. Past assessments and management settings required revision. New monitoring data on snapper abundance and age composition were needed for assessment of stock status and contemporary management procedures. In response, northern fisheries jurisdictions and the FRDC commissioned tactical research to develop a survey / observer structured fishery monitoring program and critically evaluate the potential use of data. A total of 39 data sets and a range of analyses were used in this process.

Statistical analyses of commercial fishery catch rates quantified variances to establish abundance indicators from structured monitoring. The variances were used to calculate the number of survey / observer days required to monitor tropical snapper catch rates (e.g., standardised number of fish caught per unit area swept by trawling). This result was required to ensure accurate monitoring of catch rates and fish ages so the data were directly aligned for estimation of fishing mortality or, possibly, biomass.

The Northern Territory trawl shot-by-shot data had the lowest variance of the fisheries analysed. The trawl data suggested 50 observer days (≈ 100 trawl shots) would provide sufficient monitoring power to detect a 20% hypothetical decline in standardised catch rates in the Arafura Sea. The Queensland Gulf of Carpentaria trawl data was supplied on a daily basis (without individual shot data) and suggested that four times as many observer days would be required. Monthly records from trap and line fishing had the highest variances. Trap and line methods required more than 100 observer days per sector, for detecting hypothetical catch rate declines of 40%. Use of fine-scale shot-by-shot unit data with effort measures would reduce the calculated number of survey monitoring days.

Age frequencies were analysed by choosing the approximate median age of the commercial catch of each species, and examining the proportions of fish that were older than this age. The analysis accounted for variation between fishing days, whereby predominantly young fish can be caught on some days and predominantly older fish on others. The precision of estimation was determined primarily by the number of days fished for fishery catches of those sampled ages, not by the total number of fish aged. The analyses showed that reasonable precision could be achieved if catches from about 50 separate fishing days per sector could be aged and aligned against observer monitoring of catch rates. It should not be necessary to collect otoliths from more than 50 fish of any one species in any one monitoring shot. If more than 1000 fish in total of any one species are sampled, they can be subsampled by scientists so that no more than 1000 fish of each species have to be aged.

To aid future evaluation of management strategies, a population modelling tool was developed to simulate the population dynamics of the six species and evaluate potential management strategies. The model allowed for migration between regions, annual recruitment variation, and user-specification of the frequency of monitoring (in years) and the number of fishing days sampled in each monitoring year.

The modelling indicated starting points for MSE projections whereby populations may be currently at or above sustainable target limits ($1.2B_{MSY}$ or egg production > 50% virgin (Hansford, 2008)), but have potential for overfishing in future if the Queensland and Northern Territory total allowable catches (TACs) are filled. Biomass estimates from modelling were in broad agreement with previously published estimates from trawl surveys (Ramm, 1997a).

The project proposed a monitoring regime for fishing within survey-structured locations every four years in each sector. From the analyses and consideration of total harvest tonnages, the following candidate indicator species were suggested in order of priority for each sector:
1. WA Kimberley waters: Red emperor and Goldband snappers. Saddletail snapper also occurred in substantial numbers in these waters, but was not targeted by fishers.
2. Timor Reef waters: Goldband, Saddletail and Red Emperor snappers.
3. Arafura Sea: Saddletail, Goldband, Red Emperor and Crimson snappers.
4. Gulf of Carpentaria: Crimson, Saddletail, Red Emperor and Mangrove Jack snappers.

Commercial, fishery-dependent data on golden snapper did not provide sufficient power to develop critical fishery indicators for this species. Alternative monitoring, possibly concentrating on the inshore fishery, would be required.

The analyses highlighted the importance of recording all catch data at fine scale (i.e. location and effort for each trawl, trap or line catch unit). Commercial logbooks should be reviewed and made consistent across jurisdictions. Future monitoring will require strategies to reduce variances and to provide consistent guidelines on when, where and how sampling is undertaken. Any structured fishing for monitoring will need to ensure spatial coverage of the stocks and have unbiased pattern. Because the most likely candidate survey methodology will employ the use of finfish trawl apparatus, ongoing communication with this sector is essential. Management, scientists and industry need to promote the information required to improve assessment of the stocks.

The population modelling tool developed in this project should be used and maintained for testing monitoring, assessment and management procedures. The model is operated by a user-friendly graphical user interface. It could be further developed to assess any proposed marine zoning, inshore fishing grounds and expanded to include tropical snappers from Queensland east coast

and Western Australia Pilbara waters. We believe that the hierarchical model used within the tool, covering all species and regions, can provide a more accurate assessment of the stocks as a whole compared to analysing each species and jurisdiction separately. Regions for which greater amounts of data are available can inform the model on appropriate values for important population parameters such as natural mortality rates and vulnerability to fishing in regions where data may be lacking. Also, species that are more data-rich can provide information on annual recruitment for data-poor species. The modelling tool could be adapted for a larger study for other important tropical fish, such as mackerel, threadfin salmon and barramundi.

This project has described data, methods, analyses and empirical management measures for tropical snappers. It has also highlighted how to apply quantitative methods in setting sustainable harvest and fishing effort. The work contained in this report has national significance for assessment and management of commercial target species across northern Australia. Consistent and aligned cross-jurisdictional monitoring and management is a priority.

**KEYWORDS: Age frequencies, Catch curves, Catch rate standardisation, Fishery management, Lutjanidae, Monitoring, Population modelling, Simulation, Tropical snapper.**

## 2   ACKNOWLEDGMENTS

## 3   BACKGROUND

In September 2007 the Northern Australian Fisheries Committee (NAFC) resolved to develop a Harvest Strategy Framework to guide the management of tropical snapper species across northern Australia. NAFC is comprised of executive directors from the fisheries management agencies of Western Australia, Northern Territory, Queensland and Australian Governments. NAFC had a key role in delivering the Harvest Strategy Framework and coordinating the overall management of fisheries resources across northern Australia. NAFC had developed a strategic vision for northern fisheries, and the adoption of a harvest strategy approach was the key to delivering that vision.

A fisheries harvest strategy sets out both the monitoring and management required to achieve both the biological and economic objectives of the northern fishery. The purpose of this framework was to define the discrete management components of the fishery and thus the scale at which management interventions needed to be set to achieve an overall set of defined objectives. A harvest strategy aims to provide greater certainty for fisheries managers and industry through an open and transparent process.

The following are the overall objectives of the draft red snapper harvest strategy framework (Hansford, 2008):
   (i)   To facilitate the overall management of the northern Australia red snapper fishery within a multi-jurisdictional management framework,
   (ii)  To ensure the sustainability of stocks of red snappers in northern Australian waters whilst maximising economic efficiency of commercial fisheries for the species,
   (iii) To ensure the sustainability of fish taken incidentally while targeting red snappers, and
   (iv)  To minimise interactions between the fishery and threatened, endangered and protected wildlife.

The strategy was planned for the Gulf of Carpentaria and Arafura Sea finfish trawl sectors, the Northern Territory demersal and Timor Sea trap and line sectors, and the Western Australian Northern (Kimberley) Demersal Scalefish sector. Figure 1 outlines these sectors, the stratification used in the project and the spatial distribution of harvests. Further fishery description can be sourced from government status reports (Handley, 2010; Newman et al., 2010; Roelofs, 2010; Roelofs and Stapley, 2004).

This project was proposed to develop the methods and data tools required for monitoring and managing fishing activity according to the biological and economic conditions of the tropical snapper fisheries. The project was developed primarily with fisheries resource managers (end users and beneficiaries) through NAFC and the Northern Management and Science Working Group (NMSWG). NMSWG met in Brisbane 26–27 November 2007, and meeting outcomes have formed the basis of this project. The project outputs (monitoring methods and data tools) will address the challenge to improve the management of tropical red snappers to ensure their sustainability and facilitate cost efficient co-management.

Figure 1 Spatial 1° distribution and stratification of commercial tropical snapper harvests, 2003–2009. The Northern Australian fisheries were stratified from west to east as: a) Northern Demersal Scalefish fisheries off the north-west coast of Western Australia (Kimberley sector), b) Timor Reef Fishery and adjacent southern fisheries (Timor sector), c) Arafura Sea Demersal and Trawl fisheries (Arafura Sea sector), d) western Gulf of Carpentaria Demersal and Trawl fisheries (west GoC sector), and e) eastern Gulf of Carpentaria trawl fishery (east GoC sector). The data represent commercial logbook records between 2003 and 2009. Fishing methods were line, trap, and trawl. For industry confidentiality, the area of each 1° circle marker is determined by cubic interpolation of logarithm transformed harvest (in kg). Harvest includes the six tropical snapper species.

The tropical snapper fisheries in Northern Australia target six key Lutjanid species: Crimson snapper, *Lutjanus erythropterus*; Saddletail snapper, *L. malabaricus*; Red emperor, *L. sebae*; Golden snapper, *L. johnii*; Mangrove jack, *L. argentimaculatus*; and Goldband snapper, *Pristipomoides multidens*. Species pictures appear in Appendix 6—Table 26 on page 102. The fisheries have had a long and varied history (Blaber et al., 2005; Ramm, 1994).

Foreign fishing by Chinese, Japanese, Indonesian, Korean, Taiwanese, Thai and Soviet vessels dominated harvests in Northern Australian waters between 1950 and 1990. Foreign harvests were mostly taken from the Arafura Sea and north Western Australian waters (Appendix 5—Figure 46 and Figure 47 on page 101), reaching 4200 t and 2600 t respectively (Figure 2). Foreign fishing operations were only licensed after the declaration of the Australian Fishing Zone (AFZ) in 1979. In 1991, foreign vessels were prohibited to fish in Australian (AFZ) waters. Unreported illegal fishing by foreign vessels continued after 1991. Most of this illegal foreign fishing was considered to be directed at sharks with limited catches of on tropical snappers (ABARES, pers. comm., 2009). In 2007, illegal foreign fishing was significantly reduced, possibly due to Australia's increased surveillance and increased fishing costs; less than 10% of apprehended vessels in 2007 were targeting reef fish (NAFM, pers. comm., 2007).

Over the decade 2000–2010, Australian commercial fisheries developed to the stage where 500–1000 t of tropical snappers were taken annually from each sector (Figure 2). Harvests of Crimson, Saddletail and Goldband snapper were also taken by Indonesian trawlers and line boats in waters adjacent to the AFZ (Arafura Sea). In 2002 this harvest was calculated to be of the order of 3000 t (Blaber et al., 2005). Crimson and Saddletail snapper from southern Indonesian waters of the Arafura Sea were shown to be genetically related to their counterparts in the AFZ (Blaber et al.,

2005; Fry and Milton, 2009; Salini et al., 2006). This relationship was not apparent for Goldband snapper (Blaber et al., 2005; Ovenden et al., 2002; Ovenden et al., 2004). The Australian recreational harvest was estimated to be minor compared to the commercial sectors, with about 60 t, 150 t and 110 t of tropical snappers taken annually from Queensland Gulf of Carpentaria, Northern Territory and Western Australian inshore and offshore waters respectively (Henry and Lyle, 2003; Higgs, 2001; Higgs et al., 2007).

For Australia's tropical snapper fisheries there is a fundamental need to obtain better data and understanding on the status of stocks. Previous workshops and working groups have applied a number of stock assessment techniques (Blaber et al., 2005; Ramm, 1994; Ramm, 1997b). The results highlighted uncertainty in sustainable harvest, with annual estimates below and above current tonnages. The assessment work highlighted some of the following questions and problems:

– Were historical collections of data inadequate for stock assessment?
– Were records of Indonesian fishing unreliable?
– What were the impacts from Indonesian fishing vessels bordering the Australian Fishing Zone?
– Are catch rates related to abundance? Commercial trawling using sonar and global positioning systems increase fishing power (catchability). In addition, informed fishing using these techniques can compound hyperstability (i.e., conceal changes in abundance).
– Were the unreported tonnages taken by foreign fishing fleets large?

In 2007 the Northern Stock Assessment Group held a tropical snapper workshop to identify means of overcoming current data issues (Buckworth, 2007). It was considered that fisheries management needs would be met by critical indicators from fish age data, with these ultimately placed into a harvest strategy framework (management procedure). The workshop developed a research plan with indicative costs to design a monitoring program using commercial vessels. In response, this project has developed a statistical outline for a quadrennial monitoring program. The project has tested data collection within a virtual simulation (management strategy evaluation) of fish population dynamics and management control rules. The results support the development of a monitoring program to improve long term profitability and sustainability of tropical snapper fisheries.

Figure 2 Historic annual harvests (tonnes) of the six key tropical snappers. Post 1990 data were sourced from Australian commercial fishing operations only, using compulsory logbooks. Harvest data pre-1991 include foreign vessels and are indicative (unverified) tonnages only. Note assumptions on foreign harvests in Data section 6.2.

# 4   NEED

The northern Australian tropical red snapper fisheries between the Kimberley and Cape York comprise six key species from the family Lutjanidae (*Lutjanus erythropterus*, *L. malabaricus*, *L. sebae, L. johnii*, *L. argentimaculatus*, and *Pristipomoides multidens*). Status reports indicated about 2000–3000 tonnes per year of tropical snappers were caught across northern Australia, with a landings value of $9–12 million. The stock range of the Crimson and Saddletail snappers extends into Indonesian waters, with significant landings and overfishing by trawling outside of Australia's Fishing Zone (Blaber et al., 2005). Illegal foreign fishing has also occurred in the AFZ (http://www.daff.gov.au/fisheries/iuu).

Limited time series of data compared to species longevity (30–40 years), and lack of collation of catch records from different sources, have compromised past analytical assessments. Improved fishery monitoring and management in the AFZ is needed to ensure the sustainability of tropical red snappers.

In September 2007 the Northern Australian Fisheries Committee (NAFC) resolved to develop a Harvest Strategy Framework (HSF; based on the Commonwealth HSF) to guide the management of red snappers across northern Australia. NAFC's Northern Management and Science Working Group (NMSWG) held workshops in late 2007 to develop the HSF and identify means of improving our knowledge on the uncertain status of tropical snappers (Buckworth, 2007). It was clear that critical indicators developed from relative abundance indices and age composition data were needed to service management decision rules in a harvest strategy framework.

The next important requirement to finalise the HSF was to design empirical (data-based) reference points and a complementary monitoring program. Analyses of the historical data held by fishery agencies (WA, NT, Qld and Australian Government) will lead to monitoring by industry vessels to provide data for the HSF. This high-priority tactical work will enhance agency collaborations and deliver the needs for sustainable and profitable stocks. The HSF will provide greater certainty for managers and industry through an open and transparent process for ongoing adjustment to management arrangements.

## 5    OBJECTIVES

1.  Analyse current monitoring and logbook data sets, as well as survey and other information, to establish whether these data provide sufficient power to develop critical indicators of fishery performance.

2.  Provide a risk analysis that examines the use of age structure and catch rate information for development of critical indicators, and response rules for those criteria, in the absence of other fishery information.

3.  Develop a monitoring program that uses commercial vessels from the fishery to provide independent data.

# 6   METHODS

## 6.1   Biological parameters

Published values of biological parameters for Lutjanid populations from aging of sectioned otoliths date back to the mid-1980s, with the earliest studies being conducted in French Pacific territories (Brouard and Grandperrin, 1985; Brouard et al., 1984; Loubens, 1980). The technique of aging from sectioned otoliths has been validated by Baker and Wilson (2001), who used bomb radiocarbon to show that the major red snapper in the Gulf of Mexico, *Lutjanus campechanus*, lives to at least 55 years of age. Although undertaken in a different part of the world, this validation

- confirms that sectioned otoliths provide more accurate estimates of age than other techniques such as reading of whole otoliths, which produces younger age estimates; and
- gives credence to the high age estimates that result from reading sectioned otoliths.

The major biological parameters required for this project are the mean weight at age, maturity at age and fecundity at age. The mean weight at age is generally derived from a combination of

- a length-weight conversion equation of the form $W = aL^b$, where $W$ denotes weight, $L$ denotes length, and $a$ and $b$ are parameters; and
- a von Bertalanffy growth curve $L = L_\infty(1 - \exp(-K(t - t_0)))$, where $t$ denotes age and $L_\infty$, $K$ and $t_0$ are parameters.

Maturity is typically expressed as a logistic function giving the proportion of females that are mature as $1\big/\big[1+\exp\{-(\log 19)(t-t_{50})/(t_{95}-t_{50})\}\big]$, which contains two parameters $t_{50}$ and $t_{95}$. Fecundity, expressed as number of eggs produced per year per mature spawning female, is typically modelled in the same way as weight, but the value of the parameter $b$ is usually higher than in the length-weight equation because older females usually produce proportionately more eggs for their weight.

A quirk of Lutjanidae is that growth parameters are sex-specific for some species but not others. Unlike some reef fish such as Lethrinids, Lutjanids are gonochores, i.e., retain the same sex for life upon maturity. We accepted prevailing views in the literature as to which species had sex-specific growth, although we needed only average values across the two sexes. We assumed growth to be sex-specific in *L. malabaricus*, *L. sebae* and *L. argentimaculatus*, and non-sex-specific in *L. erythropterus*, *L. johnii* and *P. multidens*.

For the species covered by this project, we were able to approximate mean weight at age and maturity at age from published studies of Australian populations using sectioned otoliths and fork length (Hay et al., 2005; Newman, 2002; Newman et al., 2000; Newman and Dunk, 2002; Newman and Dunk, 2003; NT Fisheries, 2011; Pember et al., 2005; Russell and McDougall, 2005; Russell et al., 2003). We did not attempt to convert to fork length from standard length as used in other publications.

Growth and maturity parameters used in this project are listed in Appendix 6—Table 26 on page 102.

We were unable to find any published values of fecundity at length for these species. We therefore assumed that fecundity at age was proportional to weight at age for female fish.

## 6.2   Fishery data and biological data

### Background

Tropical snapper data from 39 data sets and various publications were reviewed (Appendix 7— Table 27 on page 104). The data covered six Lutjanid species: *Lutjanus erythropterus*, *L. malabaricus*, *L. argentimaculatus*, *L. johnii*, *L. sebae* and *Pristipomoides multidens*. Spatially, the data ranged across northern Australian waters (Figure 1) and included Australian and foreign harvest records from fishery and independent sources; individual fish length and age data; angler tag-recapture records; fishery observer and research survey data. The data were essentially a collection of each organisation's research and monitoring. Independently, the data served to describe regional fishery performance and biology of the tropical snapper species. However, together they provided clarity on monitoring and assessment options. The following describes the data used to assess harvest tonnages, average catch rates, fish age structures and their variances in order to develop fishery indicators.

### Foreign harvests

Historical harvests of tropical snappers by foreign vessels were collated from a Microsoft Access database provided by ABARES (Appendix 7—Table 27 on page 104). The data included foreign gillnet and trawling data. Additional records of Soviet trawl harvests, held by CSIRO, were also appended (Metadata 24). The data included linking tables for fishing zones, boats, operations including spatial latitudes, longitudes and effort, and harvests. The tonnages recorded in the database were believed to be indicative only. The level of unreported foreign harvest was unknown, but the total could be of the order of 1.5–2 times that reported. Another version of the database is held by CSIRO in Hobart.

Annual summaries of total harvest were constructed to be comparable to the assumptions and data used in previous assessments (Ramm, 1994). Data tabulations were compared with corresponding values published by Ramm (1994). Values suggested by the collated database were in agreement with previous published harvests for the years 1980–1990. For the years 1972–1979 values in the collated database were substantially lower than those previously published. Harvest tonnages for these years were assumed to be as published by Ramm (1994).

Tropical snapper harvests prior to 1972 were unknown. Historic descriptions suggest small harvests for the years 1945–1958 and 1964–1971. For these small harvests, tonnages were assumed at 10% of the median harvest from 1972–1990. Japanese stern trawling 1959–1963 was reported as extensive (Ramm, 1994). For these years tonnages were assumed equal the median of the first 10 years of foreign fishing data (1972–1981). Modelling inputs for these data were structured for easy modification and sensitivity analysis.

The species resolution of the data was unreliable. Annual harvests by sector could only be summarised into broad 'red snapper' and Goldband snapper categories; as done in previous assessments (Ramm, 1994). The red snapper category included *Lutjanus* species CAAB codes 346012, 346903, 346004, 346007, 346005 and 346015. The Goldband category included *Pristipomoides* species with CAAB codes 346002 and 346901.

Division of the harvest into individual species was therefore inferred from Australian logbook data. Australian tonnages *C* by year *y* and snapper species *s* were regressed using a log-linear function of explanatory variables:

$$C_{y,s} = \exp\left(s + s.\log(h)\right),$$

where *s* was a factor for different species terms and it was given an interaction with the logarithm of total tropical snapper harvest (*h*). The model was fitted for each sector in Matlab using the 'glmfit' procedure with a Poisson error distribution, logarithmic link and the intercept term omitted ($R^2 > 0.95$). Only years with a total harvest greater than one tonne and at least three species caught were analysed. The 'glmval' procedure was used for prediction of foreign harvest by species.

### *Data for Australian catch rates*

Catch data were obtained from logbook harvest and effort records by fishing sector (Table 1). The data varied, with finer time and spatial scales reported in the trawl fisheries than the trap and line fisheries. Reporting of Northern Territory trap and line harvests changed in the mid 1990's from monthly gridded logbooks to daily logs with fine scale resolution. To enable full analyses of the Northern Territory trap and line time series, the data were all condensed to consistent monthly records. Western Australian trap logbooks were converted from monthly to daily reporting in 2008. Only monthly data were provided for analysis. Queensland GoC trawl harvest reporting changed from daily to shot-by-shot logbooks in 2006 (J. Davies pers. comm.). Only daily aggregated harvests were provided for analysis. Table 1 details the linking Microsoft Access tables required to generate the catch rate data. The only data-limiting restrictions applied were to the NT trawl data. To enable a detailed analysis using shot-by-shot effort data, records in which fishing date, vessel name or hours fished were unknown were removed. This removed 49 records, compared to the 14641 records analysed. All catch rate data for standardisation were stored in a spreadsheet, 'glmdata.xls'. Simple tabulations of all raw data were done to summarise annual total harvests by species and sector.

For the Queensland trawl data (Table 1), hourly vessel VMS position data were used to spatially investigate harvest. The VMS data were appended to logbook harvest data by linking fishing date and vessel code fields. Trawling was identified using a speed rule of between 2.5 and 4.5 knots. This rule was derived from a 4-component mixture model using the 'gmdistribution' function in Matlab (Good et al., 2007; MathWorks, 2010; McLachlan and Peel, 2000) (Appendix 3—Figure 33 on page 83). The result was verified against trawl speed data recorded in NT logbooks (Figure 34). The selected VMS data had strong correlation with Queensland logbook latitude and longitude records (Figure 35).

Table 1 Data supplied to analyse fishery catch rates. Metadata number refers to Appendix 7—Table 27 on page 104.

| Data | Qld trawl | NT trawl | NT Demersal | NT Timor | WA |
|---|---|---|---|---|---|
| Spatial sector | East GoC | West GoC and Arafura Sea | Arafura Sea | Timor Reef | Kimberley |
| Fishing method | Trawl | Trawl | Trap and line | Trap and line | Trap |
| Years | 1998–2009 | 1995–2009 | 1983–2009 | 1995–2009 | 1999–2008 |
| Catch units per vessel | Daily kg | Trawl shot kg, with swept area data | Monthly kg, with days fished | Monthly kg, with days fished | Monthly kg, with days fished |
| Spatial units | VMS : hourly latitudes and longitudes | Logbook latitudes and longitudes | Logbook grids, sized 3×3 nautical miles | Logbook grids, sized 3×3 nautical miles | Logbook grids, sized 1 degree blocks |
| Linking tables | 1. tbl Raw Data<br>2. Boat list<br>3. Lunar phases<br>4. VMS | 1. FlatFile_A16<br>2. Catch return and boat list<br>3. ID problem trawls<br>4. Species<br>5. Zones<br>6. Lunar phases | 1. FlatFile_A6<br>2. Method codes<br>3. Catch return and boat list<br>4. Species<br>5. Zones | 1. FlatFile_A18<br>2. Method codes<br>3. Catch return and boat list<br>4. Species | 1. Red snappers<br>2. Goldband<br>3. Methods |
| Metadata no. | 1 | 14 | 15 | 16 | 31 |

### Age data

The age data were collated from a number of past research projects (Appendix 7—Table 27 on page 104, metadata no: 2, 18–22, 25, 26, 32–35 and 38). A breakdown of the numbers of fish aged is given in Table 2. The majority (74%) of fish aged were from the eastern Gulf of Carpentaria and Western Australian waters. The table highlights many years where no data were available (also see Appendix 4, page 95). As a minimum benchmark, samples of at least 300 fish were used to characterise sufficient age structures of fish populations; general principles for sampling and aging suggest at least 400–500 fish (Craine et al., 2009; Sumpton and O'Neill, 2004). Appropriate numbers of fish were present in only 27% (17 of 63) of the cells with data in Table 2.

All fish ages were determined from sectioned otoliths. Fish aging methods were in accordance with internationally recognised protocols (Fry and Milton, 2009; Milton et al., 1995; Newman and Dunk, 2003; Newman et al., 2010; Rose et al., 2005). Methods included multiple otolith readings and statistics to quantify reading bias and precision. Age verification analyses were completed for all species.

Table 2 Summary of the number of fish aged by species, sector and year. No aging data were available for *L. johnii*.

| Species | Sector | 1990 | 1991 | 1992 | 1993 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2004 | 2005 | 2006 | 2008 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *L. erythropterus* | East GoC | 117 | 50 | 0 | 0 | 0 | 0 | 0 | 0 | 9 | 0 | 0 | 144 | 1135 | 285 | 0 |
| | West GoC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 16 | 16 | 0 | 0 | 0 | 0 | 0 |
| | Arafura | 42 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 20 | 0 | 0 | 0 | 0 | 0 |
| | Timor | 66 | 29 | 119 | 71 | 0 | 0 | 0 | 0 | 35 | 45 | 0 | 0 | 0 | 0 | 0 |
| | WA | 0 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *L. malabaricus* | East GoC | 151 | 0 | 0 | 0 | 0 | 0 | 7 | 17 | 0 | 0 | 0 | 41 | 1265 | 256 | 0 |
| | West GoC | 473 | 111 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Arafura | 13 | 10 | 0 | 0 | 0 | 0 | 0 | 10 | 0 | 22 | 0 | 0 | 0 | 0 | 0 |
| | Timor | 225 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 16 | 53 | 0 | 0 | 0 | 0 | 0 |
| *L. sebae* | East GoC | 53 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | West GoC | 58 | 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Arafura | 48 | 20 | 26 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Timor | 49 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | WA | 0 | 0 | 0 | 0 | 56 | 61 | 456 | 855 | 630 | 0 | 0 | 0 | 0 | 441 | 410 |
| *L. argentimaculatus* | East GoC | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 587 | 175 | 0 |
| *P. multidens* | Arafura | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 365 | 114 | 0 | 0 | 0 | 0 |
| | Timor | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 91 | 350 | 118 | 0 | 0 | 0 | 0 |
| | WA | 0 | 0 | 0 | 0 | 137 | 604 | 661 | 1116 | 531 | 0 | 0 | 0 | 0 | 443 | 440 |

## 6.3 Catch rate analyses

Tropical snapper catches from the different sectors and fishing methods were analysed to (a) compile a time series of annual standardised catch rates and (b) quantify variances for developing catch rate indicators. The statistical analyses varied with data set and used the following procedures:

1. Two-component approach combining binomial regression (GLM or GLMM) of zero versus nonzero harvest and linear mixed model (restricted maximum likelihood, abbreviated REML) on the conditionally distributed log-transformed nonzero harvests (GenStat, 2010; Mayer et al., 2005; McCullagh and Nelder, 1989; Montgomery, 1997; Myers and Pepin, 1990; O'Neill and Leigh, 2007)
2. A single GLM assuming a Poisson distribution with a logarithm link function (GenStat, 2010; McCullagh and Nelder, 1989).

The choice of procedure was determined by the frequency and contrast in zero harvests, and skewness of residuals (Table 3). The statistical software GenStat (GenStat, 2010) was used to carry out the analyses and provide standard errors for all estimates. Stepwise regression was used to select optimal parameters for consistency across models. Any influential correlations of parameters or aliasing were removed if necessary. All model fits were evaluated using the residual deviance, adjusted $R$-squared, fixed and random effects estimates against standard errors, and residual goodness-of-fit statistics. The importance of each model term was assessed formally using either $F$ or Wald ($\approx$ chi-squared) statistics. These statistics were calculated by dropping individual fixed terms from the full model. The analysis of residuals from each model supported their multiplicative form and distributions. Standardised model predictions were generated using the 'predict' and 'vpredict' commands in GenStat. Examples of the GenStat code and the resulting goodness-of-fit plots for different species and regions are provided in Appendix 3, page 80. All continuous explanatory variates were transformed to log scale, except the terms to fit the lunar cycle.

Table 3 List of statistical procedures used to standardise catch rates by fish species and sector; 1 = two component analysis, 2 = Poisson GLM and − = no data.

| Species | Qld trawl | NT trawl | NT Demersal | NT Timor | WA |
|---|---|---|---|---|---|
| *L. erythropterus* | 1 | 1 | 1 | 1 | 1 |
| *L. malabaricus* | 1 | 1 | 1 | 1 | 2 |
| *L. sebae* | 1 | 1 | 1 | 1 | 2 |
| *L. johnii* | 1 | 1 | − | − | − |
| *L. argentimaculatus* | 1 | 1 | − | − | 1 |
| *P. multidens* | − | 1 | 1 | 2 | 2 |

For the two component analyses the mean (expected *Y*) unconditioned catch rate of harvests *y* $\{0,\ldots,y\}$ was calculated by combining each component's standardised annual predictions $E(Y) = \pi E(Y|y>0)$. The first component referred to the binary response of zero or nonzero catch, with the harvest of a fish species occurring according to the probabilities *P*(caught) = $\pi$ and *P*(not caught) = 1 − $\pi$. The probability $\pi$ was fitted using a logit transformation with log($\pi$ / (1 − $\pi$)) being a linear function of the model terms. The second component for zero-truncated harvest was the bias-corrected back-transformed mean from the linear mixed model (REML). In GenStat calculations were performed and bias corrected on the log scale, and back transformed to predict mean annual standardised catch rates:

$$E(Y) = \exp\left( \begin{array}{c} \log(\pi) + \log\left(E(Y|y>0)\right) + \sigma^2_{\log(E(Y|y>0))}\big/2 \\ \pm \mathrm{sqrt}\left(\left(\mathrm{se}(\pi)/\pi\right)^2 + \mathrm{se}\left(\log\left(E(Y|y>0)\right)\right)^2\right) \times 1.96 \end{array} \right)$$

where $\sigma^2$ was the residual variance from REML, *se* were standard errors of yearly predictions, and the $\pm$ calculation was for generating approximate 95% confidence intervals. This formula assumes that the processes for generating data for the binomial and nonzero analyses were independent; no covariance was included. For simplicity, given the large residual degrees of freedom (rdf), the value of 1.96 $\approx t_{1-0.05/2,\,\mathrm{rdf}}$ was assumed to be appropriate for generating upper and lower 95% confidence limits. A bootstrapping routine was also run to compare results with those from the confidence interval formula above. For the eastern Gulf of Carpentaria *L. erythropterus*, confidence intervals produced by the formula were marginally wider than those from bootstrapping. For the purpose of this project and simplicity, the above equation was applied to all data sets.

All mean catch rates presented in this report were scaled relative to their overall mean across years. As all compulsory logbook data were analysed, the standardised catch rates represented the best unbiased estimates of the means for the data (suitably adjusted by the statistical models); with a sampling fraction of 100%.

The accuracy of commercial monitoring of tropical snapper catch rates was assessed using the predicted mean standardised catch rates, their standard errors and model residual variances. In order to statistically detect a significant change in catch rates, considerations were required for sampling different fishing seasons, areas and vessels. Power analysis was used to summarise these considerations through data variances and make recommendations on approximate sample sizes. The GenStat procedure 'asamplesize' was used to determine the number of observer days (up to a cap of 1000) for power = 0.8, size $\alpha$ = 0.1 (the probability of rejecting the null hypothesis when it is in fact true) and one-tailed *H₁* hypothesis $\mu_t < \mu_{\mathrm{refpt}}$ (GenStat, 2010). The procedure was run for detecting a 20%, 30% or 40% hypothetical drop in mean standardised catch rates. The results assumed standardised (constant) observer seasons, areas and vessels. The sample size calculations were based on residual variances from analyses detailed in Appendix 3 on page 80. Two sample size adjustments were made to account for different catch rate units between fishing sectors: 1) for the two-component analyses, sample sizes were inflated for the frequency of zeros, and 2) sample sizes were normalised to fishing days, by multiplying by the median number of days per catch unit (Qld east GoC daily trawl =1, NT shot-by-shot trawl = 0.25, Timor Reef monthly line = 14, and Kimberley monthly trap = 8).

## 6.4 Age sampling analyses

Age frequencies were analysed for selected species and years with sufficient data (Table 2 and Table 8). The analysis modelled the proportion ($\pi$) of fish that were older than a fixed age. This fixed age was chosen to be the approximate median age (i.e., the age at which $\pi \approx 0.5$) of the catch of each species, using available data. This age varied with species and fishery (Table 8). Use of the median age for each species allowed sample sizes to be compared between species.

The proportions of older fish were analysed using a beta-binomial distribution (Skellam, 1948). This model accounted for schooling of fish by age, whereby predominantly younger fish can be caught on some days and predominantly older fish on other days. The precision of the observed proportion of older fish was determined primarily by the number of days analysed, not the total number of fish aged. To use an ordinary binomial distribution, without the 'beta' component, would be to assume that the precision depended only on the total number of fish, even if they all came from the same school.

The analysis was conducted using the statistical software *R* (R Development Core Team, 2009). The beta-binomial distribution was fitted by the library 'aod' (Lesnoff and Lancelot, 2009) (Table 4).

Table 4 Example *R* code for beta binomial.

```
nFishingDays = 6 # Number of fishing days for which we have data.
nDaysTest = 6:100 # Range of days for which we want precision estimates
df = data.frame(y = y[, 2], n = y[, 1] + y[, 2]) # Set up input data.
lf = betabin(cbind(y, n - y) ~ 1, ~ 1, df, link="logit") # Fit the beta-binomial model
Mean = coef(lf) # Coefficient of logit
Se = 0.2600 # Standard error derived from the fit in "lf"; typed in by hand from results
q = qnorm(0.95) # For 90% confidence interval (0.05, 0.95)
CIUpper = ilogit(Mean + q * Se / sqrt(nDaysTest / nFishingDays)) #
#   Upper confidence limit: "ilogit" is the inverse logit function.
CILower = ilogit(Mean - q * Se / sqrt(nDaysTest / nFishingDays)) #
#   Lower confidence limit
# Combine lower and upper confidence limits to set axis ranges (no actual plot here).
plot(c(nDaysTest, nDaysTest), c(CILower, CIUpper), type="n",
 xlab="Number of fishing days analysed",
 ylab="Proportion of older fish",
 main="Estimation for L. argentimaculatus", log="x")
# Now add data to the plot.
lines(nDaysTest, rep(ilogit(Mean), length(nDaysTest)))
lines(nDaysTest, CILower, lty=2)
lines(nDaysTest, CIUpper, lty=2)
# Add legend to the plot.
legend(x="topright", inset=c(0.015, 0.025),
legend=c("Mean", "90% confidence limits"), lty=c(1, 2))
```

## 6.5  Management strategy evaluation

*Review*

Empirical management procedures based on the Commonwealth South Eastern Scalefish and Shark Fishery (SESSF) and Eastern Tuna and Billfish Fishery (ETBF) and the West Coast Demersal Scalefish Fishery (West Coast Bioregion, Western Australia) were reviewed (Davies et al., 2007; Wayte, 2009; Wise et al., 2007). These management procedures were treated as examples (not final or draft policy) to help evaluate the use of monitoring data. Aspects of them are described in Figure 3 and Table 5. General methodology for management strategy evaluation (MSE) is discussed below. Details of implementation in the modelling undertaken for this project are described in section 6.6.

*Methodology for setting future levels of fishing*

Simulation modelling for this project was based on the SESSF management procedures (Wayte, 2009, Fig. 5.1 solid line on page 18). The procedure was slightly modified: the reference point $B_{40}$ (40% of virgin exploitable biomass), which is an approximation to $B_{MSY}$ (exploitable biomass corresponding to maximum sustainable yield), was replaced by the actual $B_{MSY}$. The reference point $B_{48}$ was correspondingly replaced by $1.2 \times B_{MSY}$, which is commonly used as a proxy for $B_{MEY}$, the exploitable biomass at maximum economic yield, when economic data are incomplete; e.g., when fishers' total costs are not available.

The management strategy consisted of two parts:
- A catch-rate part, in which total allowable catch (TAC) or total allowable effort (TAE) is reduced by a constant fraction when catch rates fall; and
- An age-structure part, in which information on age-structure of the population is used to set future TAC or TAE so as to make the instantaneous fishing mortality rate, $F$, as close as possible to the rate, here denoted $F_{MEY}$, which, under equilibrium conditions, maintains exploitable biomass, $B$, at $1.2 \times B_{MSY}$. The fishing mortality $F$ is reduced if it is estimated that $B < B_{MSY}$, and the fishery is closed if $B \leq 0.5 \times B_{MSY}$. This strategy is illustrated in Figure 4.

In a multi-species fishery, where the same fishing effort is applied across several species, there are different ways to set the TAC or TAE. A precautionary approach would be to set it according to the species for which the current value of $F/F_{MEY}$ is largest. Unfortunately, this method was not found to be practical because it is subject to large experimental errors. It does not combine monitoring data for different species. In addition, some species are less abundant than others, which makes their data less precise. Therefore, we used a catch-size-weighted approach: we calculated the weighted average ratio of desired $F$ to current $F$ over the different species, where the weight given to a species was equal to its current catch size.

As implemented in the software tool (see section 6.6 below), the strategy is quite flexible because the user can set target levels for TAC and TAE, and can choose the frequency of monitoring. For example, to test the effect of a TAC alone, with no monitoring, the user can choose a level of TAC, set the TAE target very high, and choose a long time between monitoring episodes (e.g., 50 years).

Extensive management and stakeholder consultation post-project is required to test many alternative management procedures. In this project, fishing and management were assumed to operate independently in each region, with no cross-jurisdictional management (e.g., fishers were not free to cross regional boundaries to wherever fishing was most profitable across the area occupied by all of these fisheries). It is desirable to explore cross-jurisdictional management.
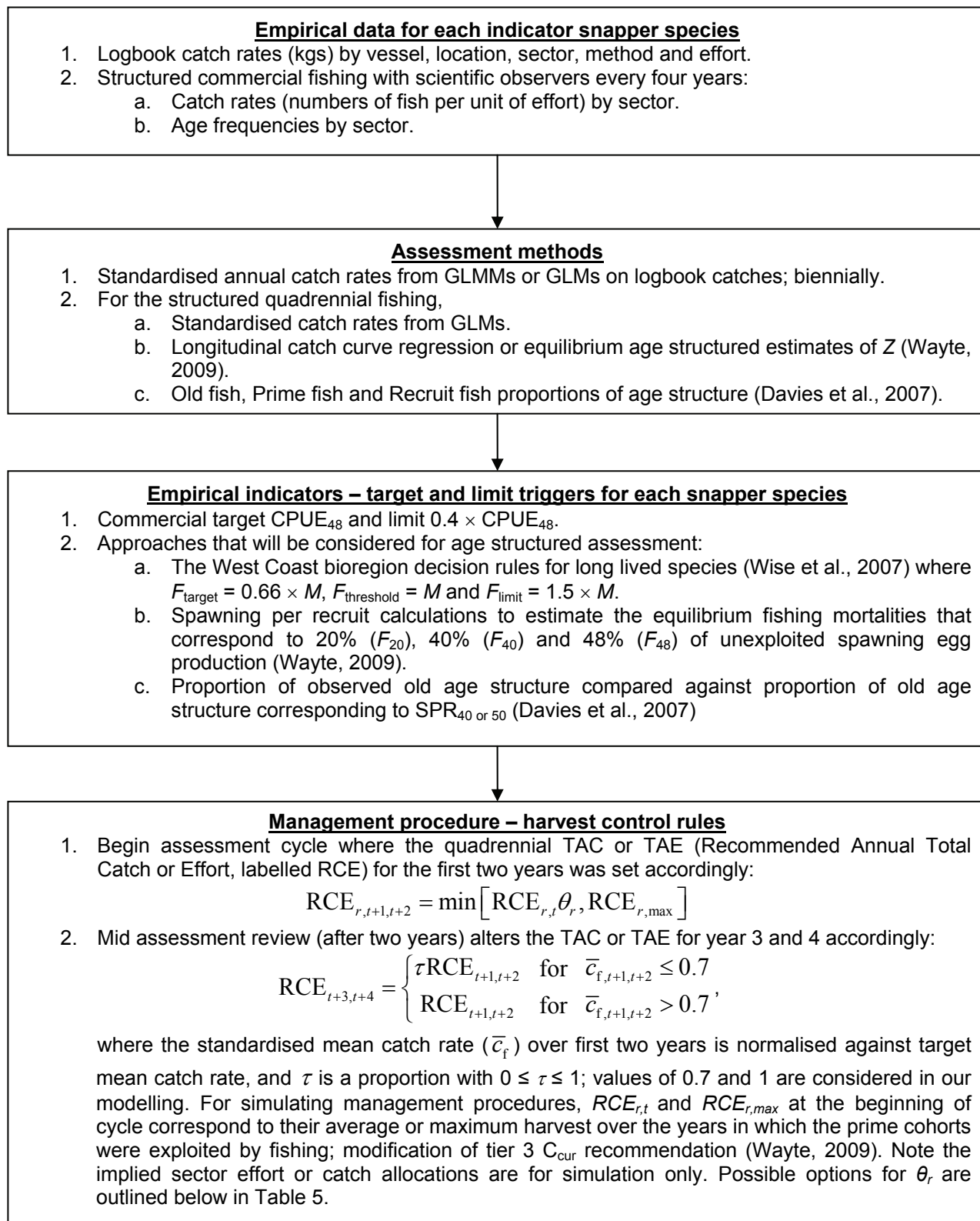
---

**Empirical data for each indicator snapper species**
1. Logbook catch rates (kgs) by vessel, location, sector, method and effort.
2. Structured commercial fishing with scientific observers every four years:
    a. Catch rates (numbers of fish per unit of effort) by sector.
    b. Age frequencies by sector.

---

**Assessment methods**
1. Standardised annual catch rates from GLMMs or GLMs on logbook catches; biennially.
2. For the structured quadrennial fishing,
    a. Standardised catch rates from GLMs.
    b. Longitudinal catch curve regression or equilibrium age structured estimates of $Z$ (Wayte, 2009).
    c. Old fish, Prime fish and Recruit fish proportions of age structure (Davies et al., 2007).

---

**Empirical indicators – target and limit triggers for each snapper species**
1. Commercial target $CPUE_{48}$ and limit $0.4 \times CPUE_{48}$.
2. Approaches that will be considered for age structured assessment:
    a. The West Coast bioregion decision rules for long lived species (Wise et al., 2007) where $F_{target} = 0.66 \times M$, $F_{threshold} = M$ and $F_{limit} = 1.5 \times M$.
    b. Spawning per recruit calculations to estimate the equilibrium fishing mortalities that correspond to 20% ($F_{20}$), 40% ($F_{40}$) and 48% ($F_{48}$) of unexploited spawning egg production (Wayte, 2009).
    c. Proportion of observed old age structure compared against proportion of old age structure corresponding to $SPR_{40 \text{ or } 50}$ (Davies et al., 2007)

---

**Management procedure – harvest control rules**
1. Begin assessment cycle where the quadrennial TAC or TAE (Recommended Annual Total Catch or Effort, labelled RCE) for the first two years was set accordingly:

$$\text{RCE}_{r,t+1,t+2} = \min\left[ \text{RCE}_{r,t}\theta_r, \text{RCE}_{r,\max} \right]$$

2. Mid assessment review (after two years) alters the TAC or TAE for year 3 and 4 accordingly:

$$\text{RCE}_{t+3,t+4} = \begin{cases} \tau\text{RCE}_{t+1,t+2} & \text{for } \overline{c}_{f,t+1,t+2} \le 0.7 \\ \text{RCE}_{t+1,t+2} & \text{for } \overline{c}_{f,t+1,t+2} > 0.7 \end{cases},$$

where the standardised mean catch rate ($\overline{c}_f$) over first two years is normalised against target mean catch rate, and $\tau$ is a proportion with $0 \le \tau \le 1$; values of 0.7 and 1 are considered in our modelling. For simulating management procedures, $RCE_{r,t}$ and $RCE_{r,max}$ at the beginning of cycle correspond to their average or maximum harvest over the years in which the prime cohorts were exploited by fishing; modification of tier 3 $C_{cur}$ recommendation (Wayte, 2009). Note the implied sector effort or catch allocations are for simulation only. Possible options for $\theta_r$ are outlined below in Table 5.

Figure 3 Example components for management procedures.

Table 5 Example options for $\theta_r$, the multiplier for TAC or TAE in response to monitoring.

Lower values for $\theta_r$ taken from WA management model (Wise et al., 2007):

$$\theta_r = \begin{cases} 1.1 & \text{for} & F_r \leq F_{r,\text{target}} \\ 1 & \text{for} & F_{r,\text{target}} < F_r \leq F_{r,\text{threshold}} \\ 0.9 & \text{for} & F_{r,\text{threshold}} < F_r \leq F_{r,\text{limit}} \\ 0.5 & \text{for} & F_r > F_{r,\text{limit}} \end{cases}$$

SESSF tier 3 model:

$$\theta_r = \frac{1 - \exp\left(-F_{r,\text{RBC}}\right)}{1 - \exp\left(-F_{r,\text{CUR}}\right)}$$

Modification of ETBF model:

$$\theta_r = \overline{c}_{\text{f},r,4\text{yr}}\,\alpha \, ,$$

where $c_{\text{f}}$ was the mean standardised catch rate over the last four years normalised against target catch rate CPUE$_{48}$, and $\alpha$ was a further adjustment based on the proportion of observed old age structure compared against proportion of old age structure expected when SSB was at 40 or 50% (Davies et al., 2007).
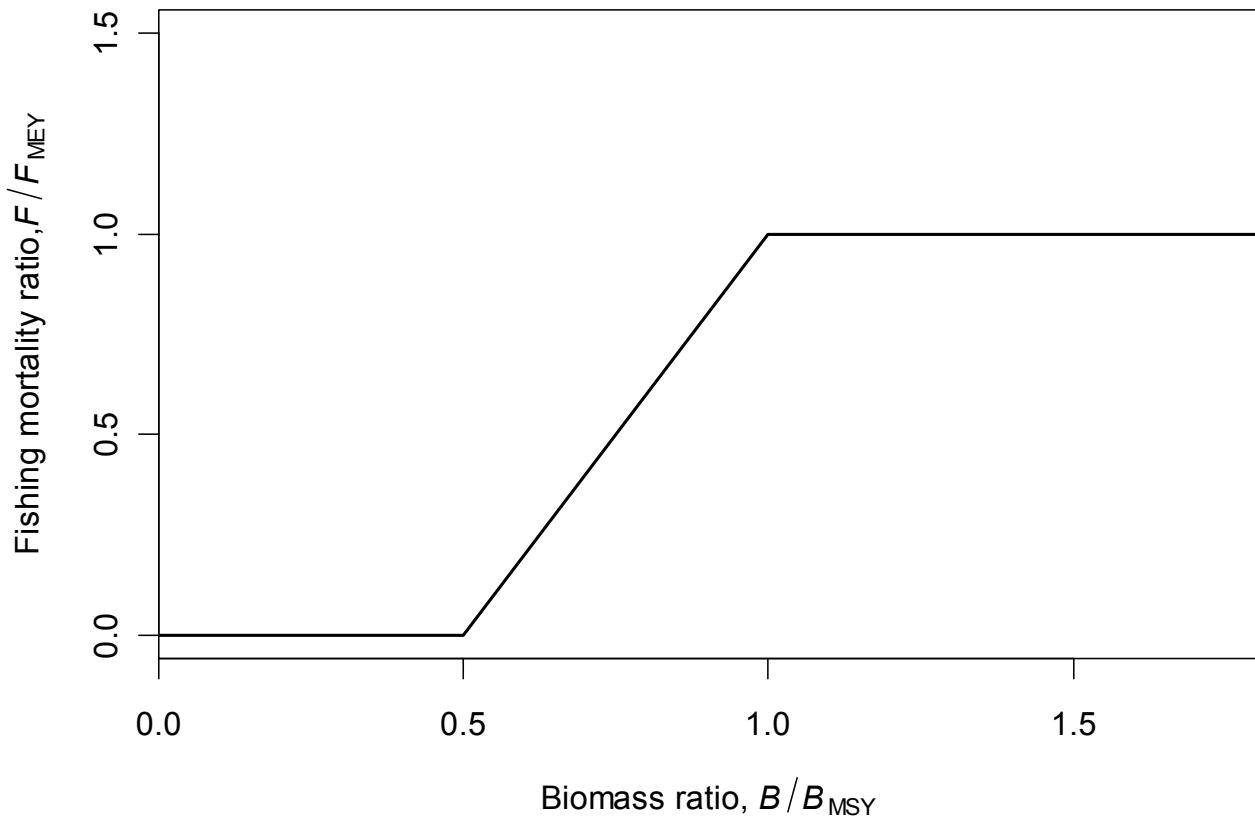


Figure 4 The procedure adopted in this project for setting future fishing mortality from information on age-structure. According to the apparent current biomass $B$, the instantaneous fishing mortality rate, $F$, is set to $F_{\text{MEY}}$ if $B \geq B_{\text{MSY}}$, zero if $B \leq 0.5 \times B_{\text{MSY}}$, and an intermediate linear function of $B$ if $0.5 \times B_{\text{MSY}} < B < B_{\text{MSY}}$. (following Fig. 5.1 of Wayte, 2009).

***Future catch rates***

Catch rates for mid assessment review (after 2nd year of four year cycle) were assumed to be monitored independently of age structure, e.g., using logbook data. The trial management strategy involved choosing a reference year with desirable catch rates, and if the catch rate fell much below the reference value, the TAC and TAE were reduced by a pre-determined fraction until they were reset after the next age-structure monitoring episode. By using catch rates independent of age-structure monitoring, catch-rate monitoring could, if desired, be conducted more frequently than age-structure monitoring.

We allowed an option to set the reference catch rate to some fraction of the rate in the reference year, in case the full catch rate in that year might not have been sustainable in the long term. As an example, in our simulations we took 1995 as the reference year in all regions, and set the reference catch rate to 65% of the 1995 catch rate. If future catch rates fell below 70% of the reference catch rate, TAC and TAE were reduced to 70% of their pre-existing values (i.e., $\theta_r$ = 0.7 in Figure 3 and Table 5). The combination of setting the reference catch rate at 65% of the 1995 catch rate and the action catch rate at 70% of the reference catch provided remedial action below about 45% of the 1995 catch rate. Such settings might be appropriate if the 1995 population status were close to virgin and action were required below about 40% of virgin levels (a common proxy for $B_{MSY}$).

Standardised catch rates from quadrennial monitoring were not used in the simulations. They could be used in future if they were found to be more accurate than standardised catch rates calculated from commercial logbook data. If longitudinal catch curves are used in future (see sections 7.4 and 9 below, pages 56 and 69), they will have to be scaled by catch rates. Because the monitoring catch rates are calculated from the same source as the aging data, catch rates from monitoring may be better suited to this purpose than catch rates from logbook data. Standardised catch rates from monitoring can also be made more accurate by using data on trawl speed, distance, net size and spread. These swept are variables will allow for possible biomass calculations. For non-trawl sectors, detailed trap or line specifications could be used.

***Future age structures and calculation of future population status***

Age structure is monitored by sampling the catches for a pre-determined number of days, aging the fish, and recording the results in an age frequency distribution, which gives the number of fish present in each age class. The number of fish sampled in the simulations is an effective sample size rather than an actual sample size. Use of effective sample sizes takes into account the schooling behaviour of fish, whereby fish of the same or similar age may school together, and environmental effects whereby fish of different ages may prefer different habitats (Pennington and Vølstad, 1994). Methods of estimating the effective sample size per shot or per day in future sampling are described in sections 6.4 above and 6.6 below.

Externally set values are used for population parameters (instantaneous natural mortality rate $M$, productivity parameter $r_{max}$, and vulnerability parameters $a_{50}$ and $a_{95}$; see definitions below). In the software tool, these values can be set by the user (see section 6.6 below). The user can investigate the consequences of making the 'true' values differ substantially from those found during the tuning process.

The parameter $r_{max}$ is used in the stock-recruitment relationship, for which we chose the form of Beverton and Holt (1957), parameterised as

$$R/R_0 = \frac{r_{max} \, e/e_0}{1 + (r_{max} - 1) \, e/e_0}, \tag{1}$$

where $R$ denotes number of recruits (age 0+) to the population, $e$ denotes egg production, subscript $0$ denotes virgin-population values and $r_{max}$ is the recruitment compensation ratio (Goodyear, 1977). This recruitment relationship is described in more detail in section 6.6 below.

'Vulnerability' in this report refers to the combination of gear selectivity and fish availability. The most vulnerable fish (usually old fish) are assigned a vulnerability of 1. Other (usually younger) fish have age-dependent vulnerability between 0 and 1, in order to account for the possibilities that (a) they may be absent from some locations that are being fished; and (b) when they are present, the gear may have a lesser chance of catching them.

This project used a logistic vulnerability function:

$$V_a = 1 / \left[ 1 + \exp\left\{ -(\log 19)(a - a_{50})/(a_{95} - a_{50}) \right\} \right],$$

where $V_a$ is the fraction (between 0 and 1) of the full fishing mortality to which fish of age $a$ are exposed, and 'exp' and 'log' are the exponential and natural logarithm functions respectively. The parameters $a_{50}$ and $a_{95}$ are the estimated ages of fish 50% and 95% vulnerable to fishing, respectively. The same vulnerability function, but with potentially different values for the parameters, is used in both the model tuning and future simulations (see section 6.6 below).

This vulnerability function increases with age. Alternative, 'dome-shaped' vulnerability functions decrease for old fish. This can happen, for example, if old fish move into deep water that is not fished. We note that the tropical snapper fishery is already in deep water (down to about 180 m). Dome-shaped vulnerability postulates a hidden spawning stock that fishers don't see, which is difficult to establish unless some method can be devised to catch these hidden fish.

For estimation of population status, the population is assumed to be in equilibrium, i.e., to have had constant recruitment and constant fishing mortality rate for many years. This assumption is obviously highly unlikely, but may suffice for the purposes of evaluating empirical management strategies. An alternative model, with variable fishing mortality and recruitment over time, could be developed in future.

The major outputs from the analysis of age structure from monitoring are estimates of the instantaneous fishing mortality rate, $F$, and the ratio of current to virgin biomass, $B/B_0$.

The fishing mortality $F$ was assumed to apply only to vulnerable fish; effects of fishing gear are accounted for in the vulnerability function. Estimation of $F$ by species and sector uses the expected number of fish of age $a \geq 0$ per annual recruit, which is equal to

$$V_a \exp\left\{ -aM - F\left( \sum_{j=0}^{a-1} V_j + \tfrac{1}{2} V_a \right) \right\},$$

where $V_a$ is the vulnerability to fishing at age $a$ (which lies between 0 and 1). This formula allows the estimation of $F$, given sample numbers-at-age, to be performed by a generalised linear model (GLM). The GLM has a Poisson error distribution, explanatory variable ($x$-variable) $\sum_{j=0}^{a-1} V_j + \tfrac{1}{2} V_a$, and offset variable $\log V_a - aM$.

From the estimated value of $F$, one can calculate the exploitable biomass per annual recruit,

$$B/R = \sum_{a=0}^{A} V_a W_a \exp\left\{-aM - F\left(\sum_{j=0}^{a-1} V_j + \tfrac{1}{2}V_a\right)\right\},$$

where $A$ is the maximum age and $W_a$ is the mean weight at age. The annual egg production per annual recruit is

$$e/R = \sum_{a=0}^{A} \tfrac{1}{2} m_a f_a \exp\left\{-aM - F\left(\sum_{j=0}^{a-1} V_j + \tfrac{1}{2}V_a\right)\right\},$$

where $m_a$ and $f_a$ are, respectively, the maturity at age (fraction of females mature) and fecundity at age (mean number of eggs produced by a spawning female in a year). By setting $F = 0$, one can calculate versions of these quantities for a virgin population, $B_0/R_0$ and $e_0/R_0$.

The recruitment ratio $R/R_0$ can be found by manipulating the stock-recruitment relationship (1). Firstly, the relationship can be written as

$$R/R_0 = \frac{r_{max}\left(R/R_0\right)\left(e/R\right)/\left(e_0/R_0\right)}{1 + (r_{max} - 1)\left(R/R_0\right)\left(e/R\right)/\left(e_0/R_0\right)}.$$

Then it can be solved for $R/R_0$ as

$$R/R_0 = \frac{r_{max}\left(e/R\right)/\left(e_0/R_0\right) - 1}{(r_{max} - 1)\left(e/R\right)/\left(e_0/R_0\right)}.$$

Finally, the critical ratios $B/B_0$ and $e/e_0$, which provide the status of the population, can be found:

$$B/B_0 = \left(R/R_0\right)\left(B/R\right)/\left(B_0/R_0\right)$$

and

$$e/e_0 = \left(R/R_0\right)\left(e/R\right)/\left(e_0/R_0\right).$$

The biomass ratio $B/B_0$ is used to set the future fishing mortality, as described above. This future fishing mortality is implemented by changing the TAC or TAE (whichever is used by the relevant jurisdiction to manage the fishery).

The above equations can also be used to calculate the maximum sustainable yield (MSY) and its associated biomass and egg production. To do this, one finds the value of $F$ that maximises the yield given by the expression

$$\left\{1 - \exp(-F)\right\} B/B_0.$$

For the modelling in section 6.6 below, we used the Matlab routine 'fminbnd' to maximise the yield.

## 6.6   Detailed population modelling and simulation

Available data, consisting of catch sizes, standardised catch rates and age-frequency samples, were used as input to an annual, age-structured population dynamic model which covered six species across six regions.  The six regions were:
1. Qld GoC, inshore
2. Qld GoC, offshore
3. NT GoC (inshore and offshore combined)
4. NT Arafura
5. NT Timor
6. WA Kimberley.

The six species were those described in section 6.1. The separation of Qld GoC into Regions 1 and 2 was undertaken because it was of interest to Queensland fishery managers, especially with regard to *L. argentimaculatus*, a species that tends to inhabit inshore areas in its juvenile phase and then migrate offshore. Data for Region 1 were, however, very limited, with no age frequencies available.

Not all species in all regions were of interest to fishery management agencies. The following region–species combinations were identified as of interest during project meetings, and were included in the model:

- GoC (Qld and NT): *L. erythropterus*, *L. malabaricus*, *L. sebae*, *L. johnii*, *L. argentimaculatus*
- NT Arafura: *L. erythropterus*, *L. malabaricus*, *L. sebae*, *L. johnii*, *P. multidens*
- NT Timor Reef: *L. erythropterus*, *L. malabaricus*, *L. sebae*, *P. multidens*
- WA Kimberley: *L. sebae*, *P. multidens.*

The population dynamic model includes both a 'tuning' phase to fit the model to standardised catch rates and observed age-frequencies, and a 'management strategy evaluation' (MSE) phase to investigate the future effects of different management strategies.

The tuning phase included estimation of the following parameters:

- Deterministic stock-recruitment parameters: we chose to use the Beverton-Holt (1957) stock-recruitment relationship, which we parameterised as

$$R = R_0 \frac{r_{\max}\, e/e_0}{1 + (r_{\max} - 1)\, e/e_0},$$

  where $R$ denotes number of recruits (age 0+) to the population, $e$ denotes egg production, subscript $0$ denotes virgin-population values and $r_{\max}$ is the recruitment compensation ratio, which is the average number of spawners produced per spawner over its lifetime when the population size is much less than virgin (Goodyear, 1977). This relationship is straightforward, always provides greater recruitment for greater egg production, and asymptotes to a maximum recruitment size of $R_0\, r_{\max}/(r_{\max} - 1)$ at infinite egg production. The other widely used stock-recruitment relationship, which we did not use, is the one of Ricker (1954), which can be parameterised as

$$R = R_0 \left(e/e_0\right) r_{\max}^{1 - e/e_0}.$$

  Under this relationship, the recruitment is a maximum at $e = e_0/\log r_{\max}$ and asymptotes to zero as $e \to \infty$, which confounds the estimation: it is difficult to tell whether low recruitment is due to low or high egg production. The Beverton-Holt relationship contains two parameters that have to be estimated: $R_0$ and $r_{\max}$. Each region-species combination was assigned a separate $R_0$ parameter, while the $r_{\max}$ parameter was species-specific, taking the same values across all regions. The 'steepness' parameter, commonly denoted $h$, is related to $r_{\max}$ by the equation $h = r_{\max}/(4 + r_{\max})$. The egg production $e$ for each species is the sum over all regions.

- Year-specific random deviation factors from the deterministic stock-recruitment relationship: these can account for environmental factors that cause recruitment to the fishery to be high in some years and low in others. For each year, a single parameter covered all regions and species. Judging from the availability and size of age-frequency samples across the various year–region–species combinations, the available data appeared insufficient to allow the preferred estimation of region-specific or species-specific recruitment deviation parameters.

- Instantaneous natural mortality rate, *M*, a separate value for each species, estimated within the model.

- Vulnerability parameters $a_{50}$ and $a_{95\,\text{diff}}$, providing the vulnerability to fishing as a logistic function of age: this function is parameterised as

$$V_a = 1 \Big/ \Big[ 1 + \exp\big\{ -(\log 19)(a - a_{50}) \big/ a_{95\,\text{diff}} \big\} \Big],$$

  where $V_a$ is the fraction (between 0 and 1) of the full fishing mortality to which fish of age $a$ are exposed, and 'exp' and 'log' are the exponential and natural logarithm functions respectively. The parameter $a_{50}$ is the estimated age of a fish that is 50% vulnerable to fishing, while the sum of the two parameters $a_{50} + a_{95\,\text{diff}}$ is the age of a fish that is 95% vulnerable. A separate pair of vulnerability parameters, covering all regions, was fitted to each species.

A list of parameters estimated by the model is given in Table 6.

We recognise that having the same vulnerability parameters cover fishing in all regions does not fully account for the different fishing methods that are used in those regions. It was generally the case, however, that a given species was fished by the same fishing method across different regions: *P. multidens* was caught mainly by trap, and the other species mainly by trawl. *L. sebae* was an exception, being caught predominantly by trap in WA and Timor, but by trawl elsewhere. Limitations of available data may still prevent a meaningful fit of different vulnerability parameters to the different regions for this species.

The model also embodied the assumption that good and bad recruitment years were common to all species and regions. Quantification of recruitment variation by region or species would require more data than were available for this project.

We note that the model formulation satisfies recommendations 1–5 under Term of Reference 1 in the third party review of the WA Northern Demersal Scalefish Fishery (Prescott and Bentley, 2009, page 9). In detail these points are the following:

1. The instantaneous natural mortality rate $M$ is estimated within the model for each species.
2. The recruitment compensation ratio $r_{\text{max}}$ (a parameter equivalent to steepness) is estimated within the model for each species.
3. Annual recruitment multipliers $R_{\text{resid}}$ are estimated within the model.
4. Catchability parameters, which scale the biomass estimates to the standardised catch rates, are estimated in the model, although they do not appear explicitly in the model formulation. For each species–region combination, the catchability estimate is simply the ratio of the geometric mean standardised catch rate (taken over all years for which catch rate data are available) to the geometric mean estimated biomass (taken over the same years).
5. Vulnerability functions (otherwise known as 'selectivity ogives') are fitted using only two parameters for each species, thereby keeping the number of free parameters in the model to a minimum.

In addition, the tuning phase estimated effective sample sizes for the age-frequency samples, which allowed these samples to be appropriately weighted relative to the catch rates. Using an effective sample size instead of the actual sample size (number of fish measured) helped to account for the effect of fish schooling by age. The effective sample size per day of fishing can also aid future monitoring of the fishery by predicting how many fishing days will be needed to attain a given precision in the age structures, as an alternative to the age sample analyses in section 6.4.

For each age-frequency sample, the estimate of the effective sample size, denoted $\hat{T}$, was derived from a multinomial likelihood and was equivalent to setting the mean deviance from a generalised linear model to 1:

$$\hat{T} = (A-1) \bigg/ \left\{ 2 \sum_{a=1}^{A} \hat{p}_a \log\left(\hat{p}_a / p_a\right) \right\},$$

where $A$ is the number of age-classes with nonzero observed frequencies present in the sample, $p_a$ is the fitted proportion of fish in age class $a$ from the model, and $\hat{p}_a$ is the observed proportion in age class $a$. This effective sample size was roughly equivalent to the size of a hypothetical sample of independent and identically distributed (i.i.d.) fish drawn from the entire population that would have the same amount of observation error as the observed sample. It accounts for the non-i.i.d. nature of fish sampled from the same locality on the same day; such fish may school by age or may prefer a particular habitat type based on their age. It also accounts for some lack of fit of the model ('process error') due to the model's necessarily being a simplification of a highly complex system of population dynamics.

An effective sample size per sampling day was calculated by dividing the effective sample size $\hat{T}$ by the number of days over which the sample was collected. Days with less than seven fish aged of a particular species were excluded from this calculation, and were assumed to have an effective sample size of 1.

Table 6 List of parameters estimated by the population dynamic model

| Symbol | Description | Distribution | Number of parameters | Bounds |
|---|---|---|---|---|
| $R_{\text{resid}}$ | Recruitment deviation factors, 1980–2009 | Lognormal | 29 | (0.2, 0.5) standard deviation of log |
| $R_0$ | Virgin recruitment numbers for region–species combinations of interest to stakeholders | Logarithmic uniform prior | 21 | (0, ∞) |
| $r_{\text{max}}$ | Recruitment compensation ratio by species, equivalent to steepness (same value *L. johnii* and *L. argentimaculatus*) | Lognormal prior | 5 | (0, ∞) |
| $M$ | Instantaneous natural mortality rate by species (same value *L. johnii* and *L. argentimaculatus*) | Normal prior | 5 | (0, 0.3 yr$^{-1}$) |
| $a_{50}$ | Age at 50% vulnerability to fishing by species (same value *L. johnii* and *L. argentimaculatus*) | Uniform prior | 5 | (2 yr, 11 yr) |
| $a_{95\,\text{diff}}$ | Age difference between 50% and 95% vulnerability to fishing by species (same value *L. johnii* and *L. argentimaculatus*) | Uniform prior | 5 | (0, 7.5 yr) |

The model also included the following parameters which, due to lack of data, had to be fixed externally and were not estimated in the tuning phase:

- Migration rates between regions: one parameter for movement from inshore to offshore in the Qld GoC, one for movement between eastern and western GoC, and one for movement between the four major regions (GoC, Arafura, Timor and Kimberley). The last parameter is at present not implemented, due to prevailing scientific opinion expressed at project meetings that there is probably minimal movement of adult fish between the major regions.
- Degree of contribution to recruitment by egg production in neighbouring regions; i.e., larval migration.
- Proportions of eastern GoC recruitment which took place inshore and offshore
- Effect of Indonesian fishing: this consists of one parameter for each region, which acts to increase the apparent natural mortality. This parameter quantifies the combination of movement of fish between the Australian and Indonesian fishing zones, and a higher rate of fishing mortality in the Indonesian zone than the Australian zone.
- The factor by which catches by foreign fishing vessels were underreported prior to 1991.

The model was tuned by Markov Chain Monte Carlo (MCMC), a mathematical method by which a large sample of different values of the parameters can be generated in order to show the range of potential outcomes. The tuning process consisted of selecting some initial parameter estimates, specifying prior distributions for the parameters, performing 'burn-in' iterations as an opportunity for the model to move to more likely parameter values, and finally performing the 'tuning' iterations to provide a random sample of parameter values.

A major advantage of MCMC is that the sampled combinations of parameter values can be reused to simulate future projections of population status. Use of MCMC also satisfied recommendation 2 under Term of Reference 4 by Prescott and Bentley (2009, page 9); they recommended MCMC in order to 'improve the estimated uncertainty of model outputs'.

Prior distributions for the MCMC are listed in Table 6 and in the Results section (Table 11, page 55). The numbers of burn-in and tuning iterations were each set to 100,000. Parameter values from every iteration were saved, but the management strategy evaluation used only every hundredth tuning iteration, i.e., a total of 1000 iterations. Convergence of the MCMC algorithm was assessed graphically by plotting the sequences of values of various parameters and of the negative log-likelihood.

The model did not incorporate data on catches by recreational fishers. This was due to both a lack of accurate data and the relatively small size of the recreational fishery in these regions. In Queensland, for example, the major recreational fishery for tropical snappers is on the east coast, especially the Great Barrier Reef. Recreational catch surveys therefore include much more data from the east coast than from the Gulf of Carpentaria. Recreational catches could be included in the model as a future development, if there is any demand for this from stakeholders, but such data would be imprecise given the current low level of monitoring of recreational catches across Northern Australia.

The MSE phase of the model projected some of the tuning simulations into the future in order to examine the effects of various management strategies. For this purpose, the user could set the following parameters. Most of these parameters relate directly to the future management of the fisheries, but others, e.g., assumed natural mortality rates, are needed in order to simulate the analysis of monitoring data and consequent feedback into fishery management. For ease of use,

they are made either species-specific or region-specific. If desired, these parameters could be defined for each region–species combination in a future version:

- Number of future years to simulate (the same for all species and all regions).
- Constant multiplier on recruitment in future years (the same over all years, species and regions): this parameter is intended to examine the potential effect of a major environmental change, such as a change to the flow-through of oceanic water through northern Australia.
- Future fishing effort (region-specific): this was expressed as a piecewise linear function of time and parameterised, for each region, as a final effort value and a number of years to get there. The final effort is specified as a multiple of the current fishing effort.
- Total allowable catch (TAC) (region-specific), summed over all species: if the effort specified above would produce a catch greater than the specified TAC, the catch is set equal to the TAC, in order that the TAC should take precedence if the potential effort is high. For ease of use, this formulation includes only TACs for all species combined, not for single species or groups of species. We also did not attempt to model a small amount of under-fill of TACs, because to date most under-filling of TACs appears to be due to insufficient fishing effort rather than logistical errors in trying to exactly fill TACs (see Table 14, page 58).
- Number of monitoring days in each monitoring episode (region-specific).
- Effective sample size of a day's monitoring, for use in sampling age structures (species-specific). This parameter allows for different schooling behaviours of species, whereby fish of similar age may school together. The species-specific nature does not allow different effective sample sizes that may result from use of different fishing methods between regions.
- Year of first monitoring, and the period, measured in years, between successive monitoring episodes (region-specific).
- Whether catch rates are calculated in the middle of the monitoring term (i.e., halfway between two monitoring episodes) and can be used as a trigger to reduce fishing effort mid-term (the same setting, 'Yes' or 'No', for all species and all regions).
- Reference value for catch rate, specified as a reference year and a fraction of that year's catch rate (region-specific). The fraction parameter was included because the fisheries are still developing and the reference-year biomass may be above the biomass corresponding to maximum economic yield (MEY). We note that it is doubtful that this is the case in the Gulf of Carpentaria (see section 7.3 below).
- Fraction of the reference catch rate below which action is taken to reduce fishing effort (region-specific).
- Multiplier for effort or TAC when action is taken on catch rate (region-specific).
- Accuracy with which future catch rates are measured (lognormal standard deviation, species-specific). This parameter is not related to the above parameters for number of monitoring days and effective sample size which are used in calculations related to age structure.
- Recruitment compensation ratios ($r_{max}$) used in analysis of monitoring data during the MSE process (species-specific; separate to the values of $r_{max}$ estimated in the tuning phase).
- Natural mortality rates ($M$) used in analysis of monitoring data during the MSE process (species-specific; again separate to the values of $M$ estimated in the tuning phase).
- Vulnerability parameters ($a_{50}$ and $a_{95\,diff}$) used in analysis of monitoring data during the MSE process (species-specific; again separate to the values of $a_{50}$ and $a_{95\,diff}$ estimated in the tuning phase).

- Annual rate of increase of fishing power (region-specific), which is not accounted for in catch rate data generated from monitoring.
- Hyperstability parameter, denoted $\gamma$ (species-specific), to provide an effect whereby catch rates from monitoring vary less than the underlying abundance in the population. Under hyperstability, the relationship between biomass ($B$) and catch rate ($Y$) is changed from straight proportionality, $Y \propto B$, to $Y \propto B^{\gamma}$, where $0 < \gamma \leq 1$.
- Effects of Indonesian fishing (region-specific) and migration (species-specific): these are formulated identically to the tuning parameters described above, but are separate values to those used for tuning.

Simulations included random, lognormal recruitment deviations from the Beverton-Holt stock recruitment relationship, with standard deviation calculated from the tuning phase.

The model was programmed in the technical computing language Matlab (MathWorks, 2010). It included a graphical user interface (GUI) for the user to set values of parameters, of which there are a large number in the MSE phase. A picture of the GUI is shown in Figure 5.

The GUI does not include convergence diagnostics for the MCMC algorithm. Ensuring convergence for every setting that the user can specify in the GUI is beyond the scope of this project.

Calculations involved in the MSE phase and the feedback from monitoring into fishery management are described in section 6.5 above.

Figure 5 Picture of the graphical user interface (GUI) for the population modelling and simulation tool.

# 7   RESULTS/DISCUSSION

## 7.1   Monitoring standardised catch rates

This section reports on 24 different statistical analyses of commercial tropical snapper catches across northern Australia. The analyses were used to gain an understanding of the variability in the data in order to establish meaningful annual catch rate indicators. The analyses focused on 1) assessing annual catch rates by species and fishing sector, and 2) quantifying model variances (measure of observation error) to determine sampling intensity for monitoring in each fishing sector.

Results of catch rate analyses are tabled in Appendix 3, page 80. The analyses explored a range of main effect and interaction terms of explanatory factors and covariates. The analyses represented biomass through year, month and area terms, and catchability through fishing effort, vessel, lunar cycle and harvest of other species. The data had no supplementary information on fishing power increase (e.g., skipper years of experience, adoption of GPS, sounders, etc). The following summarises the general characteristics of the data and analyses:

- Residual variances were generally large.
- The area variance component was large when vessel numbers were small (i.e., the trawl sectors;  Appendix 3—Table 17 on page 82 , and Appendix 3—Table 19 on page 87).
- The vessel variance component was large when vessel numbers were large (i.e. the line and trap sectors; Appendix 3—Table 21 on page 90, Appendix 3—Table 23 on page 92, Appendix 3—Table 25 on page 94).
- The variance components for fishing months were significant but less dominant with no strong seasonal patterns.
- Variances and degrees of freedom for line and trap sectors were underestimated due to the monthly data units (Appendix 3—Table 21, Table 23, Table 25). The NT line and trap time scales for recorded harvest changed over time (daily, trip and monthly). Analyses were limited to month units so that the whole time series could be used.
- Spatial area (grid cell) factors for WA monthly data were confounded with other model terms, and therefore could not all be estimated. Model splines on grid central latitude and longitudes were used to allow for some spatial changes in abundance (Appendix 3—Table 25).
- Catch rates were found to vary significantly between years ($p < 0.05$) and catches of the different snapper species were generally positively correlated. Low statistical power and non-significant year effects were evident for the NT Arafura line and trap sectors (Appendix 3—Table 21).
- Modelling covariates of other species' (Lutjanidae or other families) non target harvests may provide supplementary hidden (cryptic) catchability or effort information.

Catch rates are compared annually by species and sector in Figures 6–10. Each species' annual time-series is described and scaled relative to its mean catch rate (1 = mean catch rate). For example, a plotted value of 0.8 would indicate a catch rate 20% below the overall mean, and a value of 1.2 would indicate a catch rate 20% above the mean.

Trawl catch rates of tropical snappers from eastern GoC waters (Queensland) varied between years (Figure 6). Catch rates of *L. erythropterus*, *L. malabaricus*, *L. johnii* and *L. argentimaculatus*

were below their average in the last three years (2007–2009). Catch rates of *L. sebae* declined up to 2004 and then stabilised. Confidence intervals were tightest for *L. erythropterus*. *L. johnii* catch rates were the highly variable. Data were sparse for 2000 and 2001 fishing years. Supplementary analyses on by-product Moses snapper (*Lutjanus russellii*) showed high variation and results must be subject to very large sampling error (Appendix 3—Figure 36 on page 84).

Trawl catch rates from west GoC and Arafura Sea waters (Northern Territory) were the least variable (Figure 7). The data had good trawl shot-by-shot resolution with effort information. As in Queensland waters, catch rates of *L. malabaricus* in west GoC and *L. erythropterus* in Arafura Sea were below their mean in last three years. Catch rates of *L. sebae* declined in early years, then stabilised. *L. malabaricus* catch rates in Arafura Sea showed marginal decline. Catch rates of *L. argentimaculatus* in west GoC and *P. multidens* had increased.

Demersal line and trap fishing data in Arafura Sea (Northern Territory) had the longest time series of data from 1983 (Figure 8). For stock assessment, data with the longest time series was usually the most valuable. However, these data had the highest variance and require further verification. Despite the variability, *L. sebae* catch rates were in decline since 1999. Catch rates of *L. erythropterus*, *L. malabaricus* and *P. multidens* had increased in recent years.

Timor Reef (Northern Territory) line and trap catch rates exhibited a similar pattern to the demersal sector. *L. sebae* trap catch rates were in decline. Trap catch rates for *L. erythropterus*, *L. malabaricus* and *P. multidens* had increased. There were inconsistent trends between line and trap catch rates for *L. sebae* and *P. multidens*.

Statistical models for trap catch rates from Kimberley waters (Western Australia) were limited due to monthly harvest reporting and short time series. Over the years from 2000, catch rates had increased. This may be a result of increased fishing power, stocks recovering from foreign fishing harvest prior 1990 (Figure 2) or both.

Table 7 summarises approximate coefficients of variation (CVs) over years for standardised catch rates. In fishery modelling (as was programmed in simulations), the CV usually incorporates two components: observation error and annual variation in catchability (Francis et al., 2003). The CV values represented here were for observation error only. They can be used as a simple tool to gauge precision. However, they cannot judge the quality (accuracy) of the catch rate index (e.g., is Timor Reef line or trap catch rate more proportional to abundance?). Francis et al (2003) concluded that a typical total CV (including both components) for annual catch rates should be around 0.2. Given the high variance in data we recommend using a CV of 0.3–0.4 to gauge reasonable catch rate precision and species for monitoring. A high CV of 0.36–0.39 was documented for *L. malabaricus* from a structured demersal GoC trawl survey in 1990 (Metadata 29, 37.4% zero component; Blaber et al., 1994).

Extending from CV, residual variances were used to calculate the number of observer days (given current catch data used in analyses) required to statistically detect hypothetical reductions in catch rates by species and sector (Figure 11). These results highlight the difficult nature of monitoring catch rates. NT trawl data were most precise and calculations suggested that about 50 observer days would yield sufficient data for *L. erythropterus*, *L. malabaricus*, *L. sebae* and *P. multidens*. The 50 observer days equated to between 90 and 110 effective trawl shots. Queensland GoC trawl data suggest about 4 times as many days. However, analysis of shot-by-shot Queensland GoC trawl data would be expected to have equivalent variances and sample sizes. The residual

variances for trap and line fishing were high and only large reductions in catch rates would be significantly detected. For equal power and fine scale data, trap and line methods will required more than double the trawl observer days.

For tropical snappers, the analyses and predictions highlighted the importance of recording all catch data at fine scale (i.e., location and effort for each trawl, trap or line catch unit). Commercial logbooks should be reviewed and made consistent across jurisdictions. Future monitoring will require strategies to reduce variances and to provide consistent guidelines on when, where and how sampling is undertaken. Mechanisms to minimise vessel, gear and spatial variances need to be considered. Any structured fishing will need to ensure spatial coverage of the stocks (including heavy and lightly fished areas). The analyses have further developed techniques and showed how to structure/refine catch data for effective use as critical indicators in management. To reiterate, accurate monitoring of tropical snapper catch rates requires a minimum number of 50 fishing days to be sampled per sector each quadrennial survey.
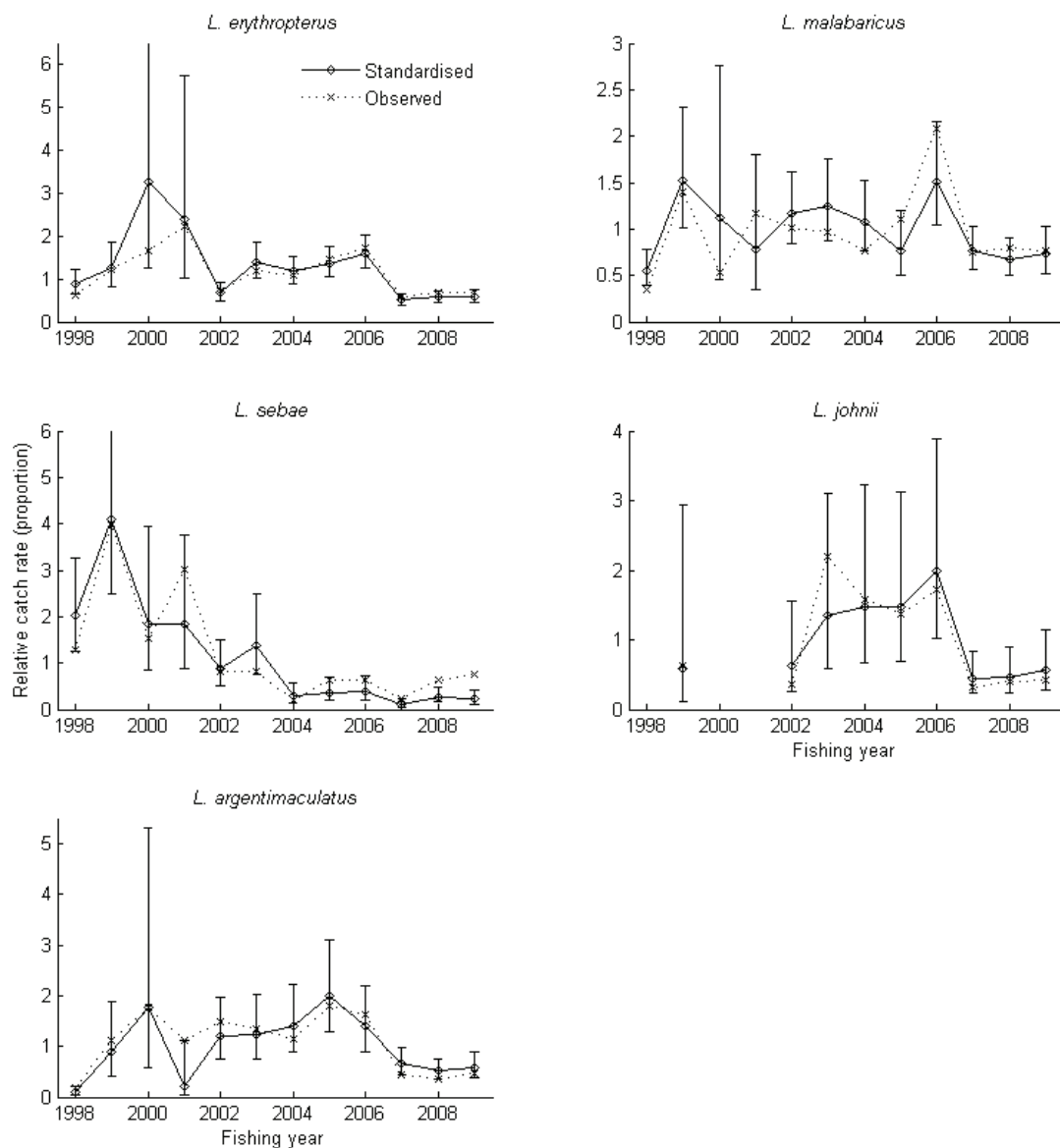


Figure 6 Observed and model-standardised average trawl harvests taken per vessel grid-site day from eastern Gulf of Carpentaria waters. Errors bars indicate 95% confidence intervals on conditional predictions. Each species' annual time-series was scaled by its mean catch rate (1 = mean catch rate; for all species, years 2000 and 2001 data were excluded from the mean benchmark due to limited fishing and data).
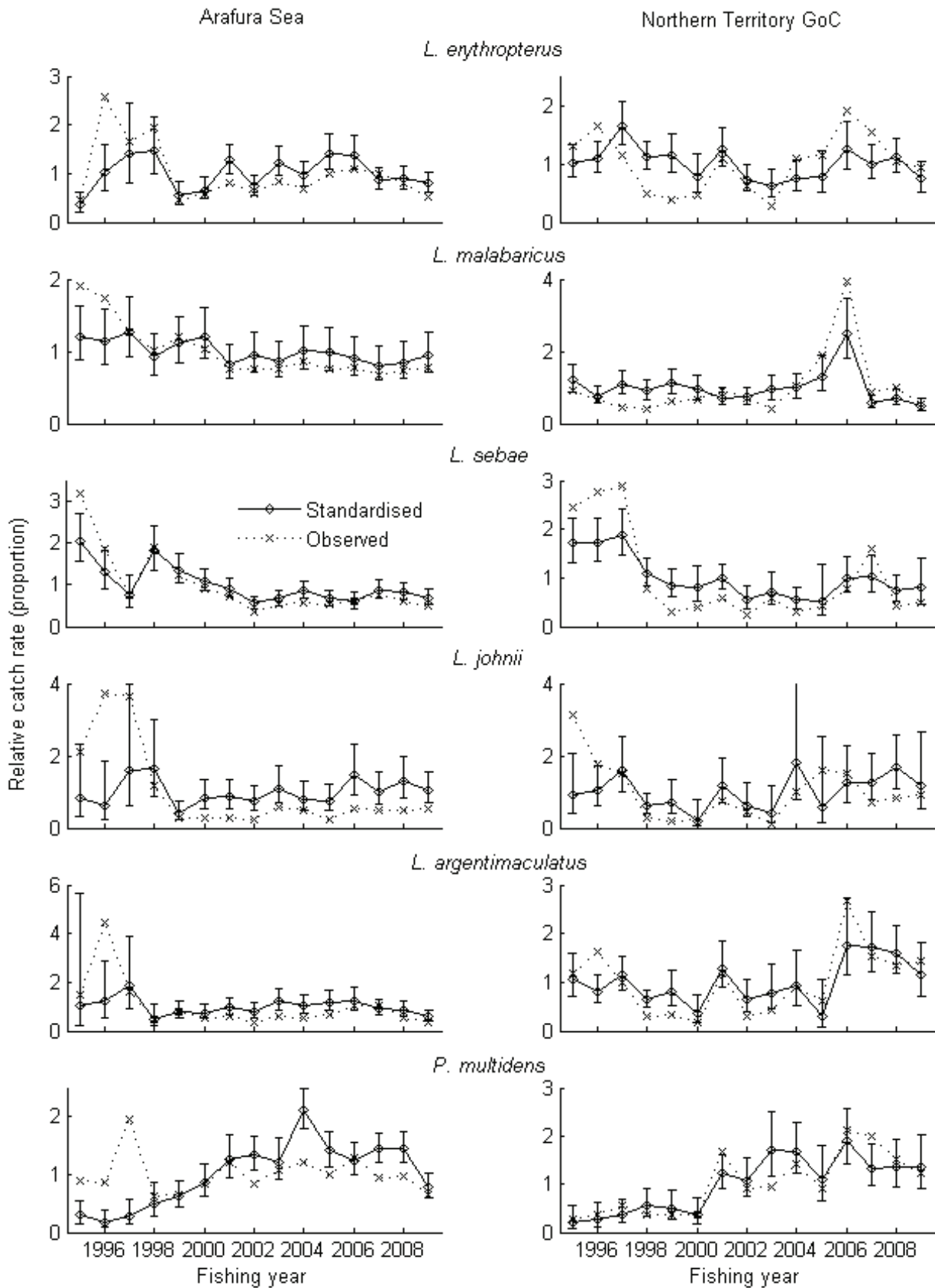
Figure 7 Observed and model-standardised average trawl harvests taken per vessel trawl shot from Northern Territory waters. Errors bars indicate 95% confidence intervals on conditional predictions. Each species' annual time-series was scaled relative to its mean catch rate (1 = mean catch rate).
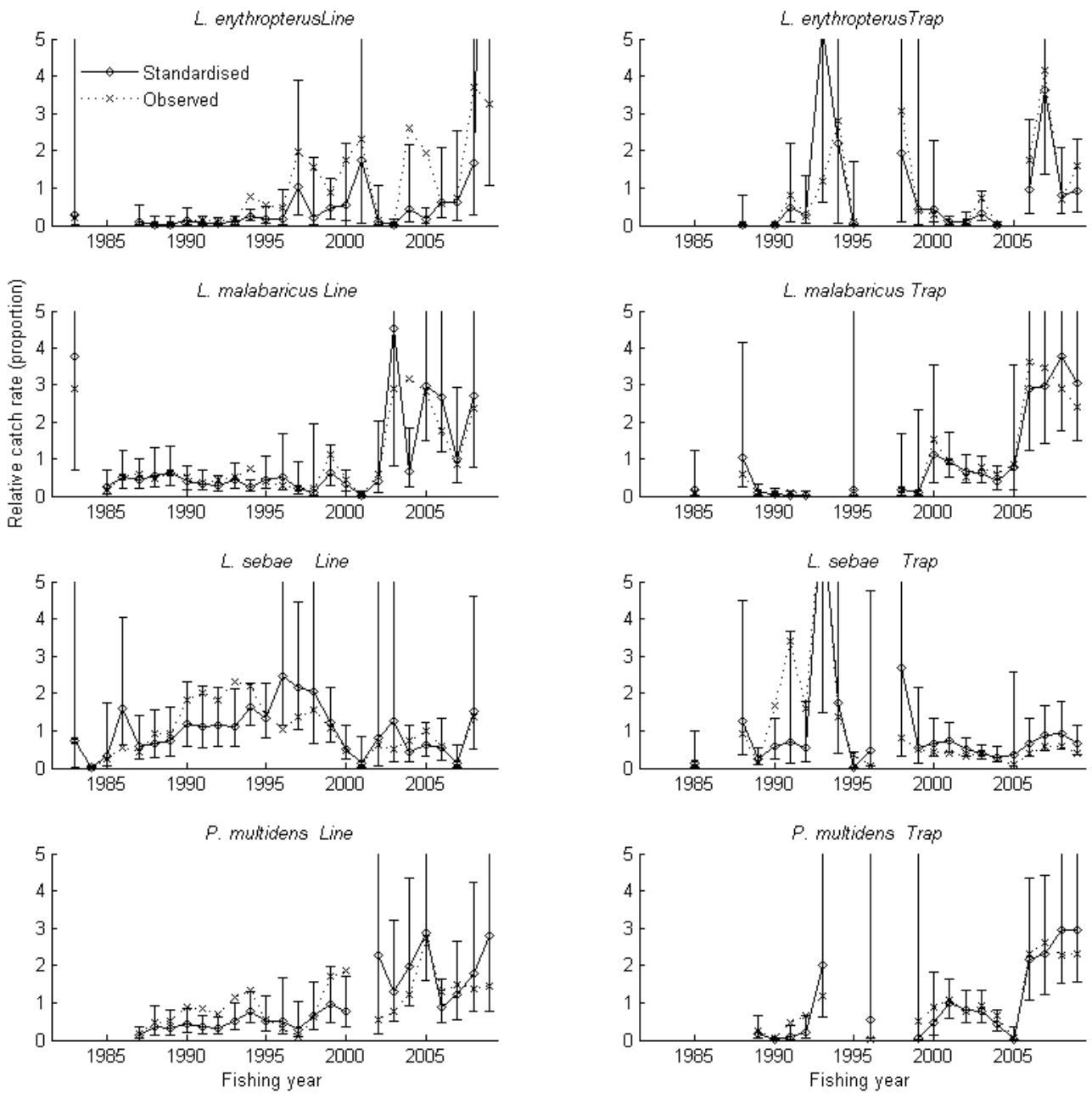
Figure 8 Observed and model-standardised average demersal (line and trap) harvests taken per vessel month from Arafura Sea waters, Northern Territory. Errors bars indicate 95% confidence intervals on conditional predictions. Each species' annual time-series was scaled relative to its mean catch rate (1 = mean catch rate).
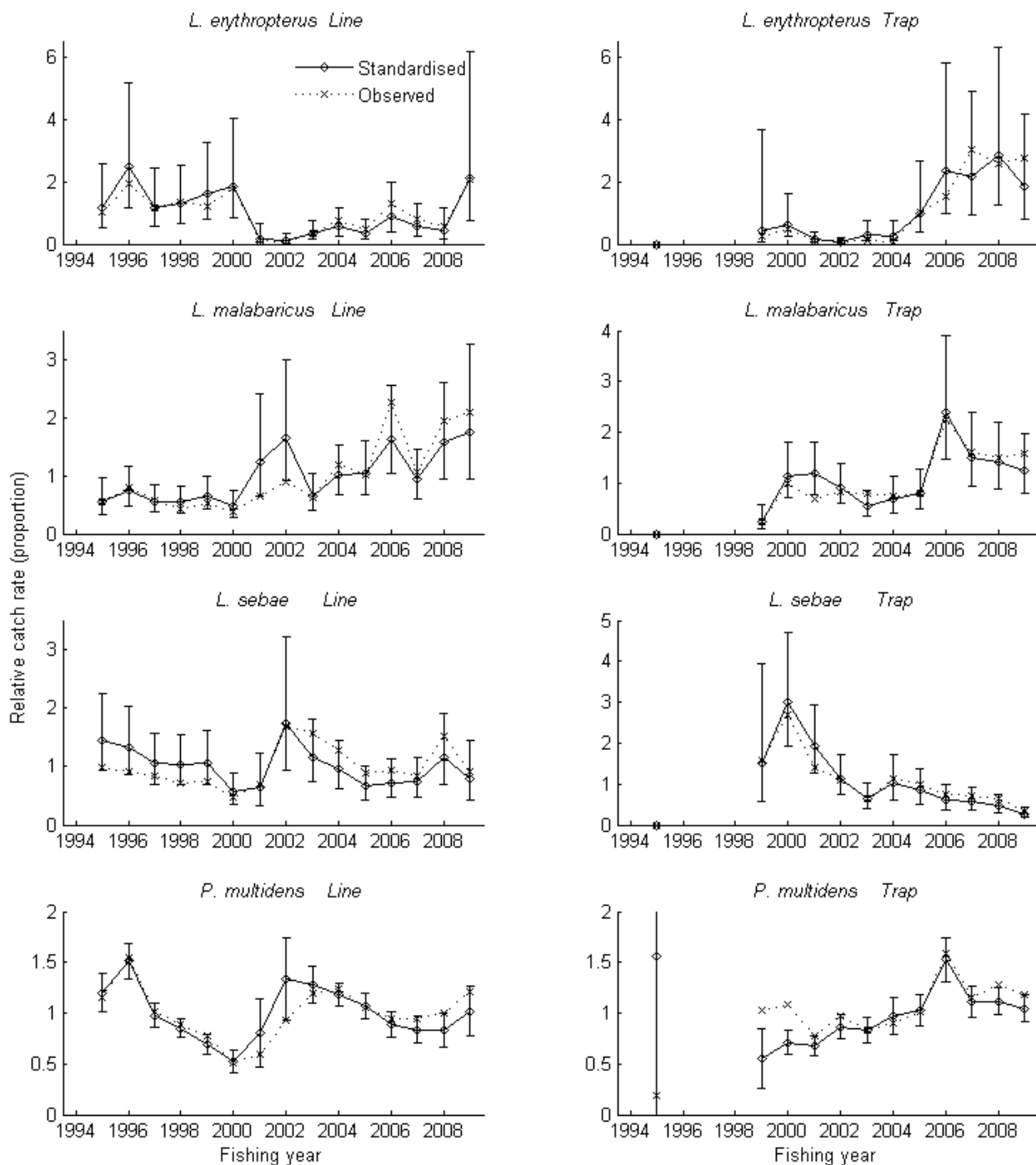
Figure 9 Observed and model-standardised average demersal (line and trap) harvests taken per vessel month from Timor Reef waters, Northern Territory. Errors bars indicate 95% confidence intervals on conditional predictions. Each species' annual time-series was scaled relative to its mean catch rate (1 = mean catch rate).
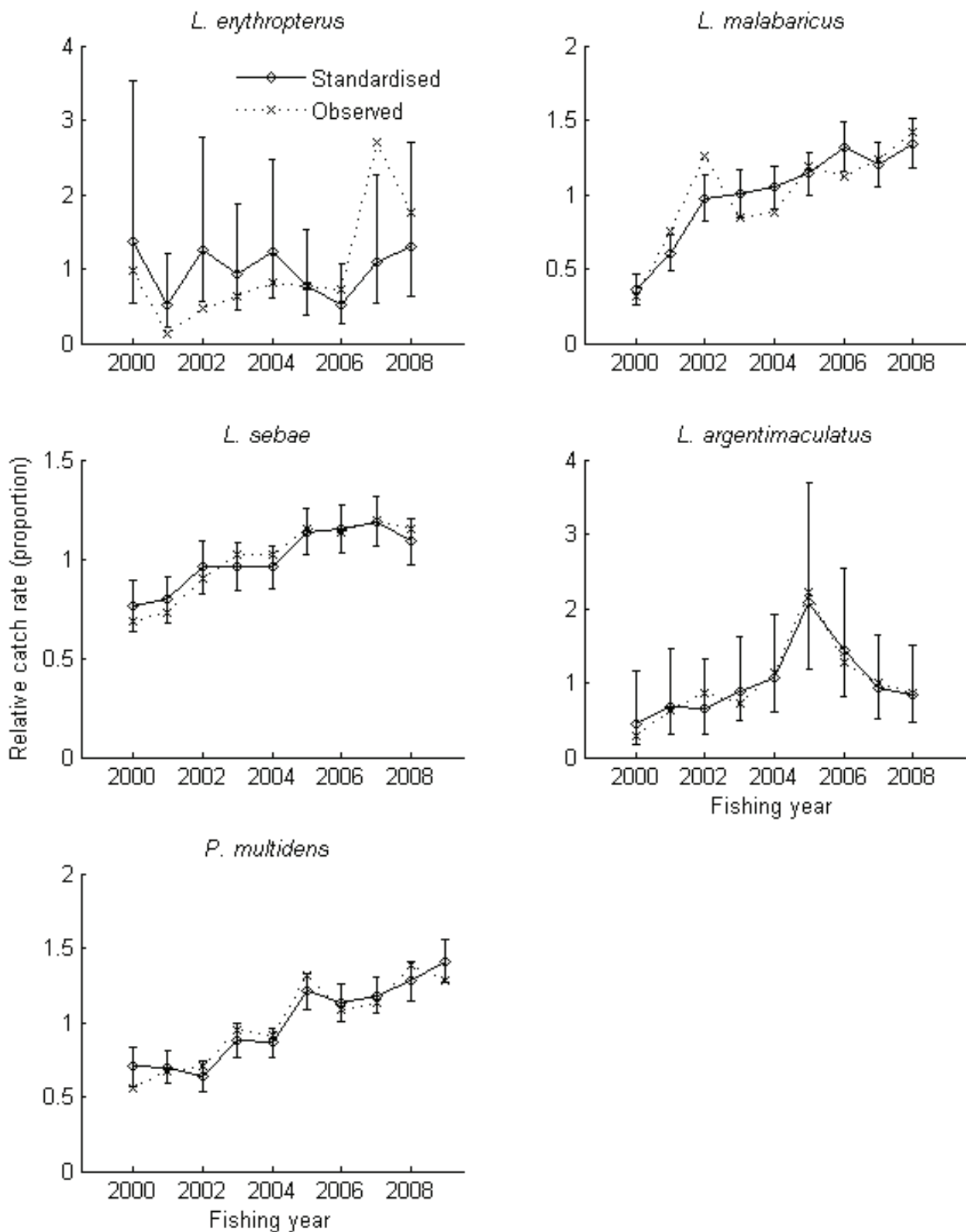
Figure 10 Observed and model-standardised average demersal trap harvests taken per vessel month from Kimberley waters, Western Australia. Errors bars indicate 95% confidence intervals on conditional predictions. Each species' annual time-series was scaled relative to its mean catch rate (1 = mean catch rate).

Table 7 Median standard errors (log scale ≈ CV) over years for model predicted annual catch rates: '–' indicates insufficient data; 'n' denotes the median number of days fishing per year by sector for the data analysed; 'n$^*$' indicates west GoC and Arafura data were analysed together. The data units analysed are shown by sector.

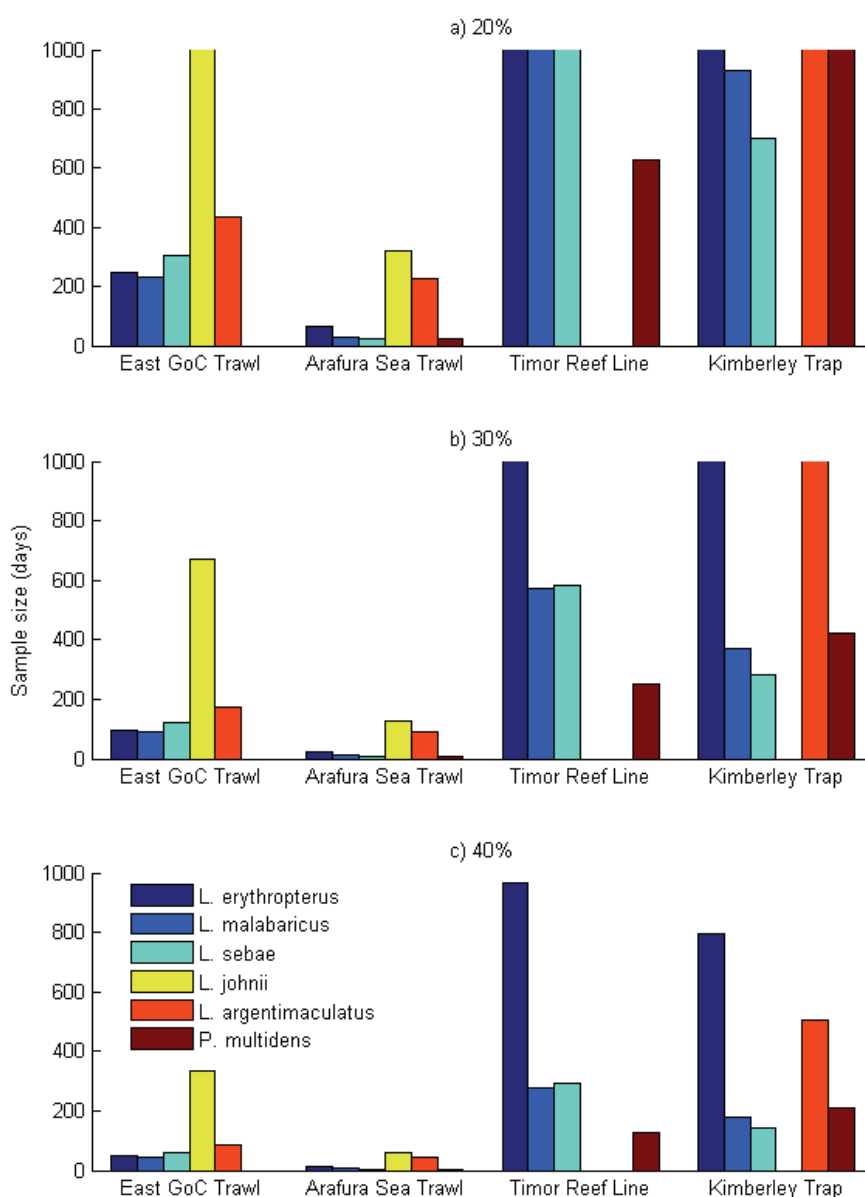| Fish species | East GoC Trawl n=348 Daily | West GoC Trawl n$^*$=34 Shot-by-shot | Arafura Sea Trawl n$^*$=224 Shot-by-shot | Timor Reef Trap n=701 Monthly | Timor Reef Line n=569 Monthly | Kimberley Trap n=784 Monthly |
|---|---|---|---|---|---|---|
| *L. erythropterus* | 0.1427 | 0.1438 | 0.1363 | 0.4791 | 0.4083 | 0.3714 |
| *L. malabaricus* | 0.1773 | 0.1595 | 0.1471 | 0.2351 | 0.2316 | 0.0736 |
| *L. sebae* | 0.3177 | 0.1816 | 0.1373 | 0.2317 | 0.2256 | 0.0630 |
| *L. johnii* | 0.3869 | 0.6203 | 0.46 | – | – | – |
| *L. argentimaculatus* | 0.239 | 0.2221 | 0.1888 | – | – | 0.3041 |
| *P. multidens* | – | 0.2 | 0.147 | 0.0890 | 0.102 | 0.0653 |



Figure 11 Approximate sample size (fishery observer days) required to statistically detect a) 20%, b) 30% and c) 40% reduction in each species catch rates by sector; *y* axes were capped at 1000. Sample size calculations were based on residual variances from analyses detailed in Appendix 3. Sample sizes were calculated for power = 0.8, size *α* = 0.1 and $H_1$ hypothesis: $\mu_t < \mu_{\text{refpt}}$. Results for west GoC trawl were similar to Arafura Sea trawl, and those for Timor Reef trap were similar to Timor Reef line.

## 7.2   Monitoring fish age frequencies

Selected age frequencies (Table 8) were analysed to determine the number of observer days required to sample fish ages with reasonable precision (confidence intervals $\approx \pi \pm 0.05$). The data sets analysed were *L. erythropterus*, *L. malabaricus* and *L. argentimaculatus* from the Queensland trawl fishery; *L. malabaricus* from the Timor Reef trap fishery; *P. multidens* from the Arafura Sea, Timor Reef and Kimberley trap fisheries; and *L. sebae* from the Kimberley trap fishery. Age frequencies were analysed by choosing the approximate median age of the catch of each species, and modelled the proportions ($\pi$) of fish that were older than this age.

Aging data from the Queensland fish trawl fishery were available from six monitoring trips between 2004 and 2006; two thirds of sampling days came from 2005. Unfortunately the age data were not recorded against the trawl shot time or day (date); they were recorded only against the monitoring trip. The Queensland analyses therefore probably underestimated the variation and confidence intervals compared to other sectors. In general, the analyses of different species and sectors resulted in wide confidence limits for the proportions of older fish (see left-hand ends of figures; Figure 12, Figure 13, Figure 14, Figure 15 and Figure 16). The confidence limits were projected to larger numbers of fishing days. The figures showed that reasonable 'age-frequency' precision can be achieved if fish catches from at least 50–75 randomly chosen fishing days can be aged in each monitoring episode (e.g., every four years).

We note from the analyses that many daily age samples appeared not to be representative. The non-representative age data were often truncated and provided misleading impressions on population dynamics. We also note that *L. malabaricus* appeared to have a strong effect of fish schooling by age, resulting in low effective sample sizes; this was especially apparent in the population-dynamic model fitting (see section 7.3, page 48). Age structures were also influenced by change in fishing locations from year to year. Further figures of age frequency monitoring are detailed in Appendix 4 on page 95.

As discussed for catch rates (section 7.1, page 36), when sampling for fish age frequencies it is important to record data at fine scale and minimise vessel, gear and spatial variances. Any structured fishing will need to ensure spatial coverage of the stocks. In general, accurate observer monitoring of tropical snapper age structures required a minimum number of 50–75 fishing days to be sampled per sector.

Table 8 Summary of data and results from beta-binomial analyses.

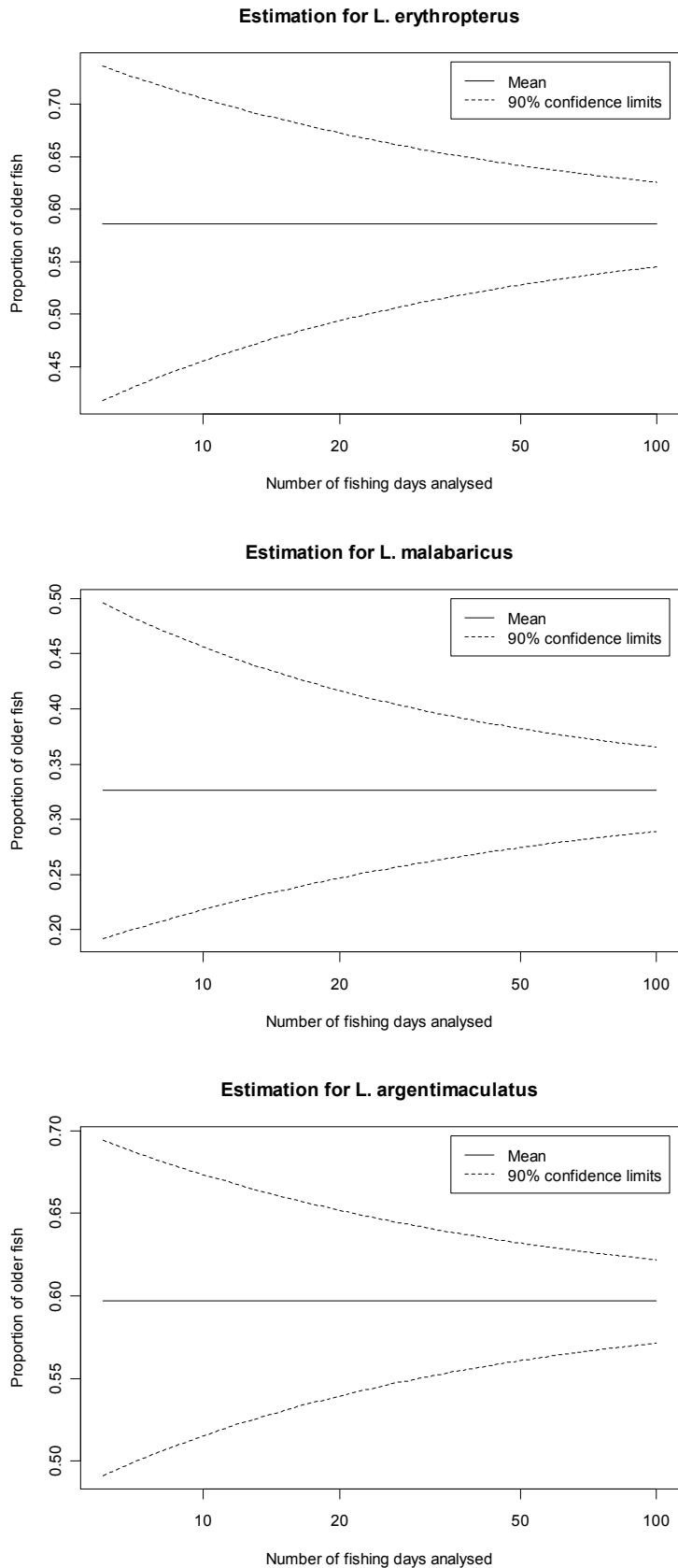| *Species* | Sector | Data analysed | Approximate median age (AMR) in yr | Proportion of fish older than AMR ($\hat{\pi}$) | Number of days sampled | Mean days sampled each year |
|---|---|---|---|---|---|---|
| *L. erythropterus* | GoC trawl, Qld | 2004-2006 | 4 | 0.58 | 36 | 12 |
| *L. malabaricus* | GoC trawl, Qld | 2004-2006 | 4 | 0.33 | 36 | 12 |
| *L. argentimaculatus* | GoC trawl, Qld | 2004-2006 | 7 | 0.59 | 36 | 12 |
| *L. malabaricus* | Timor trap, NT | 1990 | 8 | 0.52 | 14 | 14 |
| *P. multidens* | Timor trap, NT | 1999-2001 | 7 | 0.59 | 20 | 7 |
| *P. multidens* | Arafura Sea trap, NT | 1999-2001 | 7 | 0.44 | 21 | 7 |
| *P. multidens* | Kimberley trap, WA | 1995-1999 | 7 | 0.47 | 87 | 18 |
| *L. sebae* | Kimberley trap, WA | 1995-1999 | 9 | 0.52 | 39 | 8 |

Figure 12 Precision in estimation of the proportion of older fish ($\pi$) from Gulf of Carpentaria fish trawls, Queensland waters. Projected 90% confidence limits are shown as functions of the number of fishing days for which fish catches are aged.
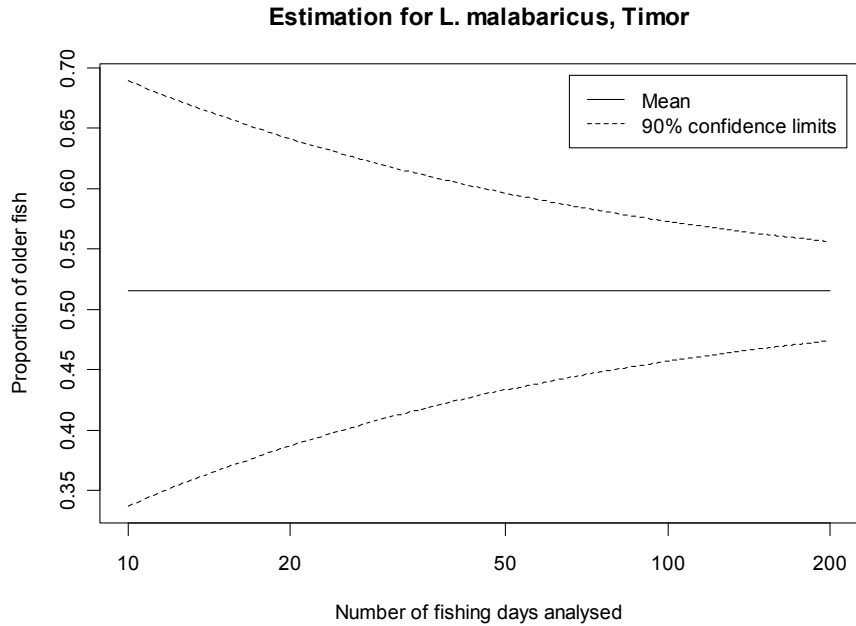
## Estimation for L. malabaricus, Timor



Figure 13 Precision in estimation of the proportion of older fish ($\pi$) for *L. malabaricus* from the Timor Reef fishery, Northern Territory waters. Projected 90% confidence limits are shown as functions of the number of fishing days for which fish catches are aged.

## Estimation for P. multidens, Arafura



Figure 14 Precision in estimation of the proportion of older fish ($\pi$) for *P. multidens* from the Arafura Sea fishery, Northern Territory waters. Projected 90% confidence limits are shown as functions of the number of fishing days for which fish catches are aged.
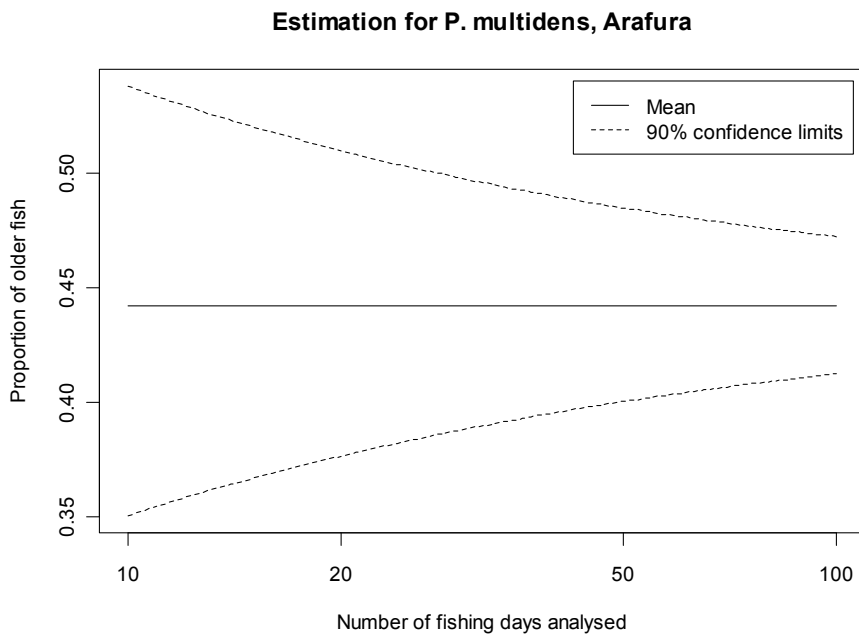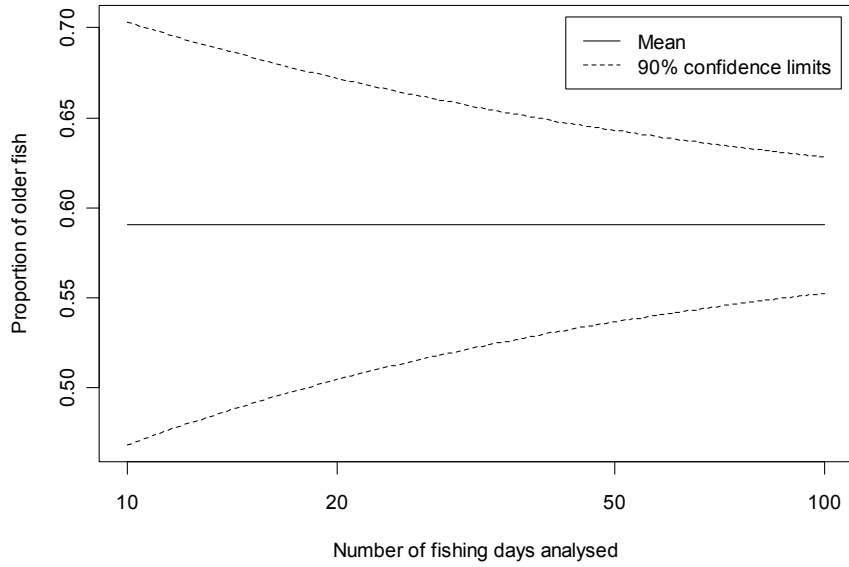
**Estimation for P. multidens, Timor**



Figure 15 Precision in estimation of the proportion of older fish ($\pi$) for *P. multidens* from the Timor Reef fishery, Northern Territory waters. Projected 90% confidence limits are shown as functions of the number of fishing days for which fish catches are aged.
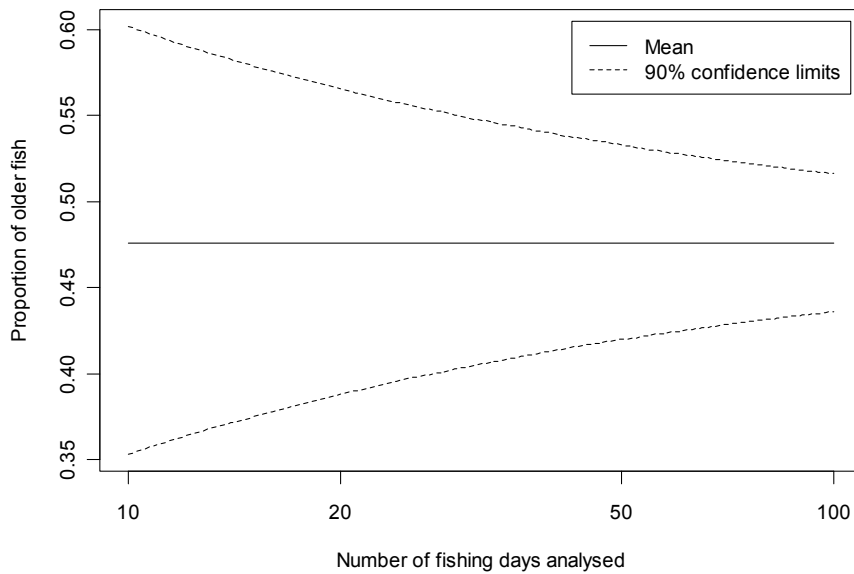
**Estimation for P. multidens, WA Kimberley**



Figure 16 Precision in estimation of the proportion of older fish ($\pi$) for *P. multidens* from the Kimberley fishery, Western Australia. Projected 90% confidence limits are shown as functions of the number of fishing days for which fish catches are aged.
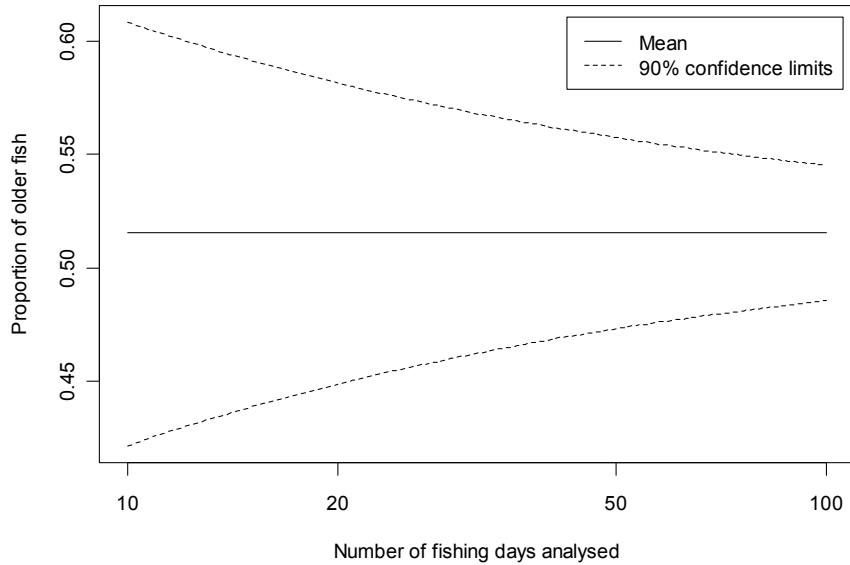
**Estimation for L. sebae, WA Kimberley**



Figure 17 Precision in estimation of the proportion of older fish ($\pi$) for *L. sebae* from the Kimberley fishery, Western Australia. Projected 90% confidence limits are shown as functions of the number of fishing days for which fish catches are aged.

## 7.3 Tuning the population model

A detailed assessment of the status of the populations of the six target species is not part of this project. Available data may, in any case, be insufficient to allow such an assessment. Nevertheless, we offer a few general comments on the results of tuning the population model.

The populations currently appear not to be overfished. On the precautionary side, however, we note the following points:

- With the exception of *L. johnii*, which inhabits shallower water than the other species, the Gulf of Carpentaria (GoC) appears to support smaller populations of Lutjanids than the other regions, and may therefore be more susceptible to overfishing. The best known fishery in the GoC is the Northern Prawn Fishery (NPF). Possibly the GoC is not as widely suitable a habitat for Lutjanids as it is for prawns, although we note that the NPF has little geographic overlap with the tropical snapper fishery (Zhou et al., 2009).
- The total allowable catches (TACs) currently in place for the Queensland GoC fishery, Northern Territory GoC–Arafura fishery and the NT Timor Reef fishery are much greater than recent catches. Dramatic increases in fishing effort in response to under-filling of these TACs could result in overfishing in future. The TACs are listed in Table 14, page 58.

Estimates of exploitable biomass are listed in Table 9. It must be noted that they are subject to very high uncertainty and may easily be in error by factors of two or more.

The biomass estimates are in broad agreement with those reported by Ramm (1997a) from trawl surveys of the Timor Reef and Arafura regions. Ramm gives an estimate of 3100 t of *Pristipomoides* spp. for the combined Timor–Arafura region, most of which would have been *P. multidens*. We note that trawl surveys may underestimate the biomass of *P. multidens* because this species favours rocky habitat that may be impossible to trawl. Ramm (1997b) quotes an

estimate of 24,000 t of 'red snapper' (comprising *L. malabaricus* and *L. erythropterus*), which presumably came from the same surveys.

Trajectories of biomass, egg production and recruitment are plotted in Figures 18–20. These show the relative effects of foreign fishing in the 1970s and 1980s, subsequent recovery, and development of the Australian fishery. Foreign fishing probably had a big effect on the populations in most regions, although because it consisted mainly of trawling it had a smaller effect in the Timor Reef region (much of which consists of ground that is not trawlable) and on the species *P. multidens* (which is currently caught mainly by trap). Figure 20 indicates that random variation in recruitment appears to have affected recruitment more than fishing has. Figure 21 plots these recruitment multipliers with 95% confidence limits from the MCMC simulations, and shows a substantial amount of uncertainty in the values of the recruitment multipliers.

Table 9 Approximate maximum likelihood estimates of exploitable biomass from model tuning, for species of interest in each region. The last column is the estimated virgin exploitable biomass ($B_0$) in tonnes. Estimates are subject to very high uncertainty, factors of the order of 2.

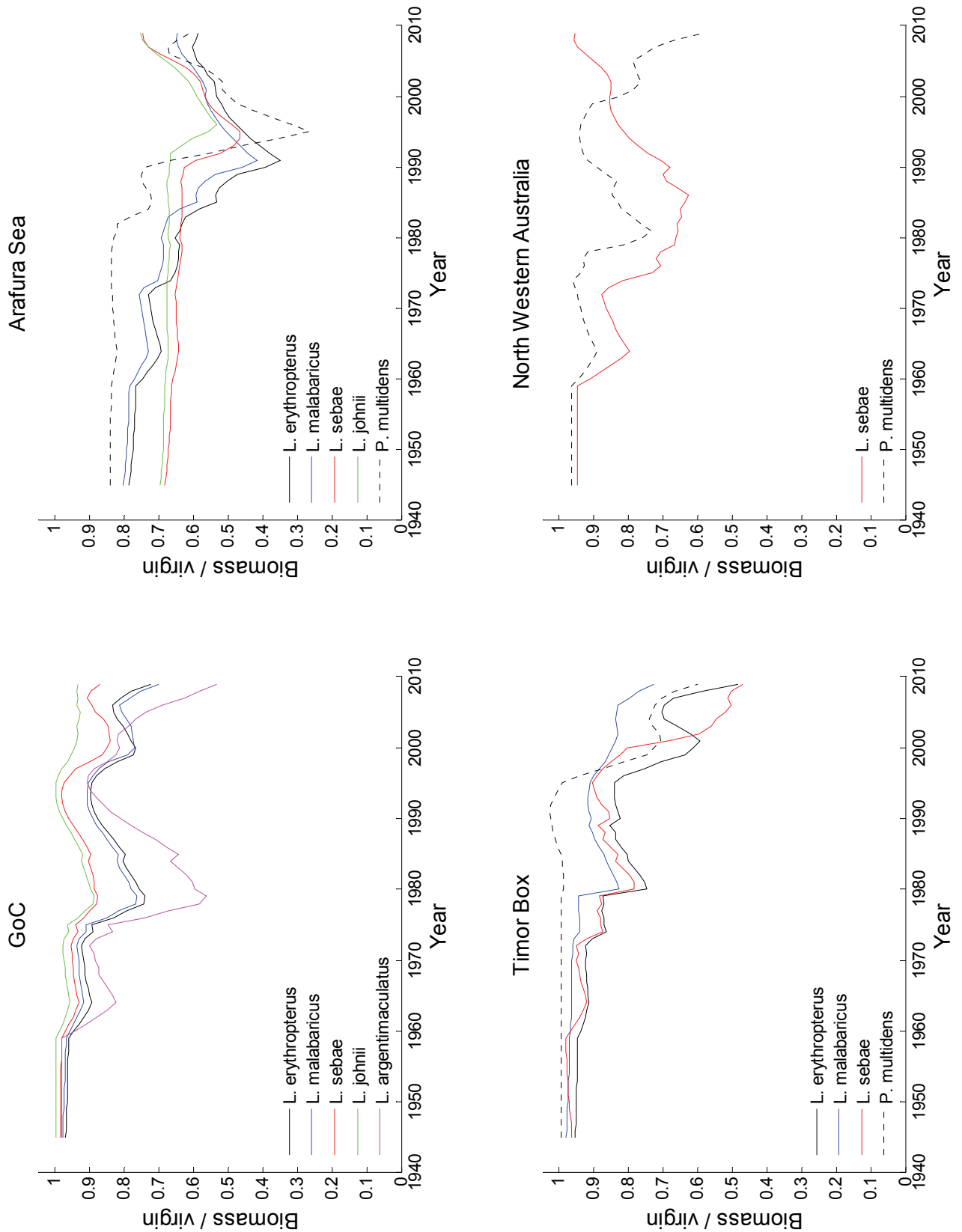| Region | Species | $B_0$ (tonnes) |
|---|---|---|
| Qld GoC | *L. erythropterus* | 2820 |
| | *L. malabaricus* | 2500 |
| | *L. sebae* | 350 |
| | *L. johnii* | 1010 |
| | *L. argentimaculatus* | 500 |
| NT GoC | *L. erythropterus* | 2060 |
| | *L. malabaricus* | 1200 |
| | *L. sebae* | 120 |
| | *L. johnii* | 110 |
| | *L. argentimaculatus* | 190 |
| NT Arafura | *L. erythropterus* | 5510 |
| | *L. malabaricus* | 27590 |
| | *L. sebae* | 1040 |
| | *L. johnii* | 560 |
| | *P. multidens* | 2640 |
| NT Timor Reef | *L. erythropterus* | 580 |
| | *L. malabaricus* | 3160 |
| | *L. sebae* | 370 |
| | *P. multidens* | 4890 |
| WA Kimberley | *L. sebae* | 8400 |
| | *P. multidens* | 3640 |

Figure 18 Approximate maximum likelihood biomass trajectories of relevant species for each region, showing the relative effects of foreign fishing and the development of the Australian fisheries.

Figure 19 Approximate maximum likelihood egg production trajectories of relevant species.

Figure 20 Approximate maximum likelihood recruitment trajectories of relevant species, showing that, compared to annual random variation, fishing appears to date to have had relatively little effect on recruitment. Nonzero recruitment deviations were included in the model only from 1980 onwards, because data from which earlier ones could be estimated were not available: recruitment is deterministic until 1980 and shows little variation for some years afterwards, due to scarcity of data.

Figure 21 Random multipliers for recruitment, estimated from the tuning phase of the model. The solid line shows the geometric mean multipliers, while the dashed lines show 95% confidence limits. Each recruitment multiplier applies to all regions and all species in a particular year. Confidence limits are wider in later years due to lack of information about age classes when they have been vulnerable to fishing for fewer years.

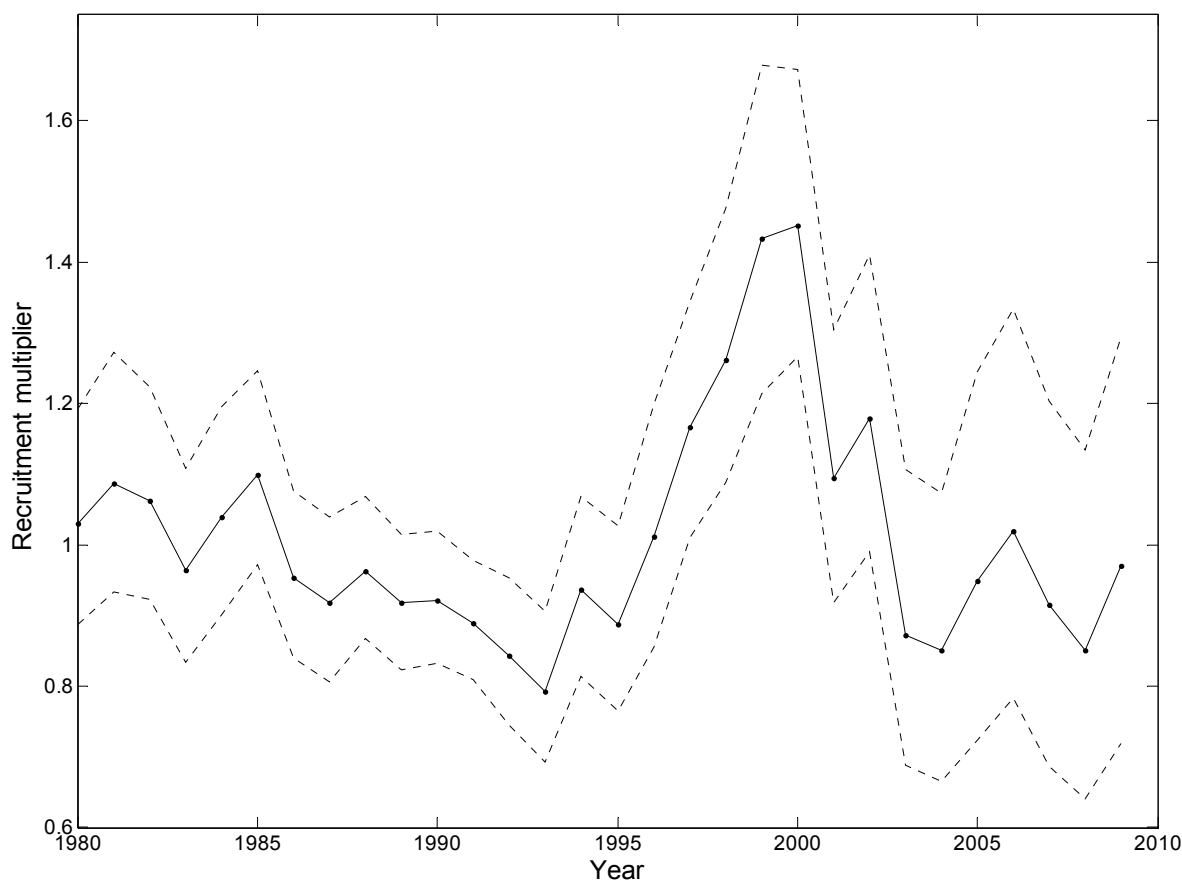Apart from growth parameters, which were available from the literature (see section 6.1, page 15), data for *L. johnii* were not sufficient to estimate population parameters. We therefore set these parameters equal to the corresponding values for *L. argentimaculatus* (the species whose life cycle is closest to *L. johnii*).

Estimates of population parameters for the six species are listed in Table 10. The estimates of the instantaneous natural mortality rate $M$ are generally in accord with published estimates (Newman, 2002; Newman and Dunk, 2002; Newman and Dunk, 2003; Pember et al., 2005; Russell et al., 2003). The exception is the estimate for *P. multidens*, which is substantially higher than the estimate of 0.104–0.139 yr$^{-1}$ calculated by Newman and Dunk (2003) from analysis of a subset of the data used here.

Parameters that had to be fixed to pre-assigned values due to lack of information are listed in Table 11, together with those used in prior distributions. Values of all the parameters in Table 11 could easily be changed in future work if desired. For example, the standard deviation of the prior distribution for $M$ could be increased from the value of 0.03 yr$^{-1}$ used here, which was chosen to roughly match the perceived uncertainty in previously published estimates.

The effective sample size (averaged over the MCMC tuning runs) of annual age-frequency samples ranged from around 1–5 (poor representation of the population) for many samples

collected in the early 1990s, to 100–300 (very good representation) for some samples collected between 1996 and 2008 in Queensland GoC and WA Kimberley. We note that low effective sample sizes are typical for fisheries data; for example, in the large study of estimating the mean length of haddock on Georges Bank by Pennington and Vølstad (1994), their Table 1 shows effective sample sizes of roughly 1 per trawl shot, often 50 times less than the actual sample sizes.

The average effective sample size per sampling day for each species is listed in Table 12. These values are a guide to the effective sample sizes that may be achievable in future monitoring. The results indicate that effective sample sizes of 10 or more per day of sampling can be expected for all species other than *L. malabaricus*. This species appears to have a high degree of schooling by age. To obtain useful information on it may possibly require an unfeasibly high number of monitoring days.

The fits to standardised catch rates are shown graphically in Figure 48, page 103. These show only the run that gave rise to the highest likelihood observed during the MCMC tuning, which is an approximate maximum likelihood fit.

Fits to age distributions are shown in Figures 41–45, pages 96–100. These figures show the large amounts of observation error present in the data for this fishery, which appear to be due to the tendency of fish to school by age and possibly a tendency for fish of different ages to prefer different habitat types.

A major uncertainty is the effect of Indonesian fishing. The parameters for this effect were fixed during the tuning (see Table 11). To resolve this uncertainty would require much better knowledge of both the level of fishing mortality in Indonesian waters and the rates of movement of fish between Australian and Indonesian waters. The authors regard it as likely that, due to the topography of the ocean floor, there is little such movement in regions other than the Arafura Sea, because the other regions have deep water separating the Australian and Indonesian jurisdictions. This view is reflected in the parameter settings used (Table 11).

Other settings of the parameters relating to Indonesian fishing could be tried in future runs of the model in order to find the levels that that would seriously affect Australian fishery management. In a worst-case scenario, if both movement rates and Indonesian fishing mortality were very high, any Australian management measures would be rendered ineffective. We emphasise that our model accounts for only the combined effect of movement and Indonesian fishing, and cannot separate the two components. To estimate the level of Indonesian fishing at which the Australian fishery becomes seriously affected would require knowledge of movement rates between the two fishing grounds.

Table 10 Estimates of population parameters, with 95% confidence limits, from the tuning phase of the model. Parameters are the instantaneous natural mortality rate ($M$), recruitment compensation ratio ($r_{max}$), age at 50% vulnerability to fishing ($a_{50}$), and the difference between ages at 95% and 50% vulnerability ($a_{95\ diff}$). Confidence limits may be unrealistically narrow due to high observation error in the inputs.

| Species | $M$ (yr$^{-1}$) | $r_{max}$ | $a_{50}$ (yr) | $a_{95\ diff}$ (yr) |
|---|---|---|---|---|
| *L. erythropterus* | 0.137 ± 0.011 | 10.2 ± factor 2.5 | 5.9 ± 0.4 | 4.2 ± 0.4 |
| *L. malabaricus* | 0.164 ± 0.014 | 9.4 ± factor 1.8 | 6.3 ± 0.3 | 6.4 ± 0.4 |
| *L. sebae* | 0.161 ± 0.007 | 36.1 ± factor 2.5 | 6.6 ± 0.2 | 2.9 ± 0.2 |
| *L. argentimaculatus*, *L. johnii* | 0.135 ± 0.012 | 87.2 ± factor 2.1 | 7.0 ± 0.4 | 4.3 ± 0.5 |
| *P. multidens* | 0.233 ± 0.011 | 25.6 ± factor 1.9 | 5.7 ± 0.1 | 1.8 ± 0.2 |

Table 11 Values of parameters that were fixed during tuning due to lack of information, and parameters used in prior distributions.

| Description | Meaning | Value |
|---|---|---|
| Underreporting | Ratio of true to reported foreign harvests | 1 |
| Indonesian fishing | Value added to instantaneous natural mortality rate to account for movement of fish between Australian and Indonesian waters, combined with higher fishing mortality in Indonesia | $0.015\ \text{yr}^{-1}$ (Arafura) Zero in other regions |
| Larval migration | Proportion of egg production contributing to recruitment in neighbouring regions | 0.2 |
| GoC migration | Proportion of total GoC population moving from east to west per year, = proportion moving from west to east | 0.03 |
| Adult migration | Proportion of total population over all regions moving westward across each region boundary, = proportion moving eastward | 0 |
| Mean prior $M$ | Mean of normal prior distribution for instantaneous natural mortality rate, $M$, for all species | $0.11\ \text{yr}^{-1}$ |
| Sd prior $M$ | Standard deviation of normal prior distribution for instantaneous natural mortality rate, $M$, for all species | $0.03\ \text{yr}^{-1}$ |
| Mean prior $r_{max}$ | Mean of normal prior distribution for log of recruitment compensation ratio, $r_{max}$, for all species | $\ln(10)$ |
| Sd prior $r_{max}$ | Standard deviation of normal prior distribution for log of recruitment compensation ratio, $r_{max}$, for all species | $\ln(10)/2$ |
| Mean prior $U_{max}$ (*L. johnii*) | Mean of normal prior distribution for highest harvest rate in any year, same for all regions | 0.105 |
| Sd prior $U_{max}$ (*L. johnii*) | Standard deviation of normal prior distribution for highest harvest rate in any year, same for all regions | 0.0475 |
| Mean prior $U_{max}$ (*L. argentimaculatus*) | Mean of normal prior distribution for highest harvest rate in any year, same for all regions | 0.18 |
| Sd prior $U_{max}$ (*L. argentimaculatus*) | Standard deviation of normal prior distribution for highest harvest rate in any year, same for all regions | 0.06 |
| Mean prior $U_{max}$ (all other species) | Mean of normal prior distribution for highest harvest rate in any year, same for all regions | 0.24 |
| Sd prior $U_{max}$ (all other species) | Standard deviation of normal prior distribution for highest harvest rate in any year, same for all regions | 0.08 |

Table 12 Effective sample size per sampling day, $\hat{T}/d$, for each species, calculated from tuning the population dynamic model. The region and year columns list the combinations on which the calculations are based; many samples had to be excluded due to lack of information on numbers of sampling days.

| Species | Average $\hat{T}/d$ | Range $\hat{T}/d$ | Region | Years |
|---|---|---|---|---|
| *L. erythropterus* | 10.5 | 1.7–20.2 | Qld GoC | 2004–2006 |
| *L. malabaricus* | 2.1 | 0.9–2.7 | Qld GoC | 2004–2006 |
| *L. sebae* | 13.6 | 8.5–17.8 | WA Kimberley | 1995–2008 |
| *L. argentimaculatus*, *L. johnii* | 31.2 | 29.1–39.7 | Qld GoC | 2005–2006 |
| *P. multidens* | 10.2 | 8.1–17.3 | WA Kimberley | 1995–2008 |

## 7.4  Management strategy evaluation

The management strategy evaluation (MSE) phase of the population model was run for eight different scenarios, which are listed in Table 13. All scenarios except Scenario 8 used the current TAC and TAE settings listed in Table 14. Parameter values that were common to all scenarios are listed in Table 15. All simulations were conducted for 50 years into the future. The first monitoring year was taken to be 2012 in all scenarios except Scenarios 7 and 8, which did not involve any monitoring; for these scenarios the first monitoring year was set to 2062 and simulations were extended for 60 years instead of 50. The mechanism of feedback from monitoring to fishery management is described in section 6.5, and the parameters and settings are described in section 6.6.

It can be seen from Table 14 that TACs in Queensland and Northern Territory waters are substantially under-filled. It is evident from the degree of under-fill that the under-filling in these jurisdictions is due to lack of fishing effort rather than logistical error in trying to fill TACs. Therefore the simulations assumed that fishing effort would increase at a moderate rate, linearly increasing to double the current effort over 10 years in Scenarios 1–6. In WA the TAE is approximately 100% filled, being slightly under-filled in 2009 and slightly over-filled in previous years.

Average total harvests over all MSE simulations are plotted in Figures 22–29. All scenarios resulted in sustainable fishing except Scenario 7 (constant TAC in Queensland and Northern Territory waters, with no monitoring), which showed major falls in the harvests (even though the fishing effort was ten times the 2009 level) and was clearly not sustainable. Scenario 8, the case of constant effort (around double the 2009 levels in Queensland and NT), performed much better. The problem with management by effort, however, is 'effort creep', whereby fishers become more efficient over time and their fishing power increases. Therefore it seems clear from Figures 22–29 that some monitoring of the fishery is needed.

Averaging of harvests over the simulation runs omitted important information, as can be seen in Figures 30 and 31, which show harvests for individual runs. To meet the needs of all stakeholders in fishery management, the harvest should not vary greatly with time. An exception could be made if biomass varied wildly and unpredictably, but that is not the case for the long-lived species in this fishery. The most notable aspect of Figures 30 and 31 was that the NT Timor Reef fishery oscillated between high catches and complete closures of the fishery. Inclusion of extra days of monitoring (Figure 31) helped only slightly. The situation was much better for the other regions, but still not ideal. Harvest also varied substantially in the Queensland Gulf of Carpentaria, although the inclusion of extra monitoring days was of some help in that case.

The oscillation of harvests was probably due to a combination of the following factors in all fisheries:
- Limited numbers of monitoring days and small effective sample sizes per day of monitoring (especially for *L. malabaricus*)
- High reference TACs (much larger than current catches, and probably larger than can be sustained)
- Long time-lag from when levels of fishing are changed to when the effects become apparent in monitoring data.
- Lack of cross-jurisdictional management, which would allow monitoring samples to be combined between jurisdictions, thereby improving the sample sizes.

The following actions could help to stabilise the harvests without demanding excessive numbers of monitoring days:

- Downweighting the contribution of species with low effective sample sizes per monitoring day (e.g., *L. malabaricus*) in the setting of future levels of fishing, when some monitoring results become available and researchers have more confidence in the estimates of effective sample size
- Establishment of lower reference TACs, above which the TACs set from monitoring data are not allowed to go
- Use of a more sophisticated catch-curve model (yet to be developed), which could provide more accurate estimates of recent fishing mortality rates than the equilibrium model
- Cross-jurisdictional management and pooling of monitoring samples across regions.

The sophisticated catch-curve model would not assume that fishing mortality had been constant for many years. It could also be 'longitudinal', meaning that it allows for year-to-year variation in recruitment and follows each year-class or 'cohort' from one monitoring episode to the next.

We note that harvests in Western Australia were very stable in all scenarios. This is due to the WA strategy of managing the fishery by effort (TAE) rather than catch (TAC), and setting the TAE sustainably. Management will still need to allow for potential fishing power increases.

In summary, monitoring every four years appeared to offer reasonable prospects of supporting management of the fishery in a sustainable manner. A minimum of 50 days of monitoring per region per four-year period is needed. A higher number of monitoring days would produce less year-to-year variation in the harvests.

Table 13 Scenarios that were simulated for management strategy evaluation. The specified instantaneous fishing mortality rates, $F$, would be reached by a combination of changes to both fishing effort and fishing power.

| Scenario number | Description | Details |
|---|---|---|
| 1 | Base case | Monitor every 4 years, 50 days per region, standardised catch rates every 2 years. Target $F$ = 2 × current in Qld and NT; time to reach it = 10 yr. |
| 2 | Fall in recruitment | Extra multiplier of 0.7 on every annual recruitment |
| 3 | No mid-term monitoring | Omit 2-year CPUE monitoring |
| 4 | More frequent monitoring | Monitor every 2 years |
| 5 | Less frequent monitoring | Monitor every 6 years |
| 6 | More monitoring days | 100 monitoring days per region |
| 7 | Constant TAC, no monitoring | $F$ = 10 × current, current TAC in Qld and NT, no change WA |
| 8 | Constant $F$, no monitoring | $F$ = 2 × current, all TACs = 10,000 t, no change WA |

Table 14 Current settings of total allowable catch (TAC, measured in tonnes) or total allowable effort (TAE, measured in days). Queensland GoC has an additional 250 t of TAC that is currently held in reserve. TAE in WA Kimberley was slightly overfilled in some recent years before 2009. TACs for 'other' species in NT have been approximated, as the formal TACs apply to a large group of species that includes some not covered in this project. The summary of % filled was based on the sectoral stratification used in the report.

| Region | Species | TAC (t) or TAE (d) | % filled in 2009 |
|---|---|---:|---:|
| Queensland GoC | All | 1250 t | 22.3% |
| NT GoC + Arafura | *L. malabaricus + L. erythropterus* | 2500 t | 33.7% |
| | *P. multidens* | 400 t | 72.1% |
| | Others | Approx. 210 t | 18.9% |
| NT Timor Reef | *L. malabaricus + L. erythropterus* | 1300 t | 18.5% |
| | *P. multidens* | 900 t | 39.9% |
| | Others | Approx. 104 t | 13.0% |
| WA Kimberley | All | 1144 d | 95.3% |

Table 15 Parameter values common to all the MSE scenarios. Time to reach target $F$ was, however, set to 1 yr for Scenarios 7 and 8, in order to gauge the effect of a truly constant $F$ or TAC.

| Description | Meaning | Value |
|---|---|---|
| Indonesian fishing | Value added to instantaneous natural mortality rate to account for combination of movement of fish between Australian and Indonesian waters, and higher fishing mortality in Indonesia | $0.015 \text{ yr}^{-1}$ (Arafura) Zero in other regions |
| Larval migration | Proportion of egg production contributing to recruitment in neighbouring regions | 0.2 |
| GoC migration | Proportion of total GoC population moving from east to west per year, = proportion moving from west to east | $0.03 \text{ yr}^{-1}$ |
| Adult migration | Proportion of total population over all regions moving westward across each region boundary, = proportion moving eastward | 0 |
| Time to reach target $F$ | Time taken for fishing mortality to move from 2009 value to future target value, to allow for gradual increases in fishing effort | 10 yr |
| Fishing power increase | Annual rate of increase in fishing power, invisible in calculation of catch rates | $0.01 \text{ yr}^{-1}$ |
| CPUE standard deviation | Assumed lognormal standard deviation of catch rates in MSE | 0.2 |
| Hyperstability parameter, $\gamma$ | Assumed hyperstability parameter in MSE; value less than 1 makes catch rate no longer proportional to biomass. | 1 |
| $M$ (*L. erythropterus*) | Assumed instantaneous fishing mortality rate in MSE | $0.14 \text{ yr}^{-1}$ |
| $M$ (*L. malabaricus*) | | $0.14 \text{ yr}^{-1}$ |
| $M$ (*L. sebae*) | | $0.14 \text{ yr}^{-1}$ |
| $M$ (*L. johnii*) | | $0.14 \text{ yr}^{-1}$ |
| $M$ (*L. argentimaculatus*) | | $0.14 \text{ yr}^{-1}$ |
| $M$ (*P. multidens*) | | $0.23 \text{ yr}^{-1}$ |
| $a_{50}$ (*L. erythropterus*) | Assumed age at 50% vulnerability to fishing in MSE | 6 yr |
| $a_{50}$ (*L. malabaricus*) | | 6 yr |
| $a_{50}$ (*L. sebae*) | | 7 yr |
| $a_{50}$ (*L. johnii*) | | 7 yr |
| $a_{50}$ (*L. argentimaculatus*) | | 7 yr |
| $a_{50}$ (*P. multidens*) | | 6 yr |
| $a_{95}$ (*L. erythropterus*) | Assumed age at 95% vulnerability to fishing in MSE | 10 yr |
| $a_{95}$ (*L. malabaricus*) | | 13 yr |
| $a_{95}$ (*L. sebae*) | | 10 yr |
| $a_{95}$ (*L. johnii*) | | 11 yr |
| $a_{95}$ (*L. argentimaculatus*) | | 11 yr |
| $a_{95}$ (*P. multidens*) | | 8 yr |
| $r_{\max}$ (*L. erythropterus*) | Assumed recruitment compensation ratio in MSE | 10 |
| $r_{\max}$ (*L. malabaricus*) | | 10 |
| $r_{\max}$ (*L. sebae*) | | 40 |
| $r_{\max}$ (*L. johnii*) | | 100 |
| $r_{\max}$ (*L. argentimaculatus*) | | 100 |
| $r_{\max}$ (*P. multidens*) | | 30 |
| ESS (*L. erythropterus*) | Assumed effective sample size per day of monitoring | $10 \text{ d}^{-1}$ |
| ESS (*L. malabaricus*) | | $5 \text{ d}^{-1}$ |
| ESS (*L. sebae*) | | $12.5 \text{ d}^{-1}$ |
| ESS (*L. johnii*) | | $20 \text{ d}^{-1}$ |
| ESS (*L. argentimaculatus*) | | $20 \text{ d}^{-1}$ |
| ESS (*P. multidens*) | | $10 \text{ d}^{-1}$ |

Figure 22 Harvest for Scenario 1 (base case), summed over all species and averaged over 1000 simulations.



Figure 23 Harvest for Scenario 2 (sustained fall in recruitment), summed over all species and averaged over 1000 simulations.
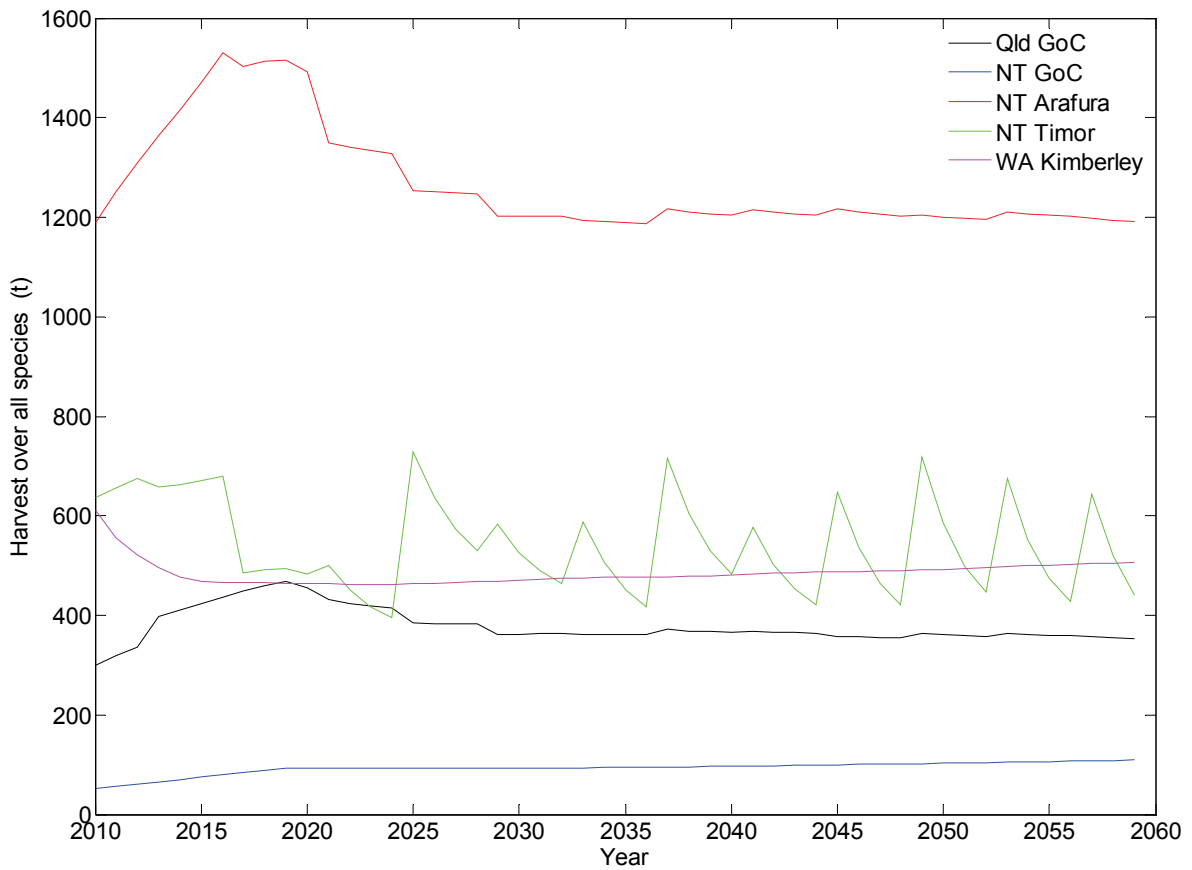
Figure 24 Harvest for Scenario 3 (no mid-term catch rate monitoring), summed over all species and averaged over 1000 simulations.
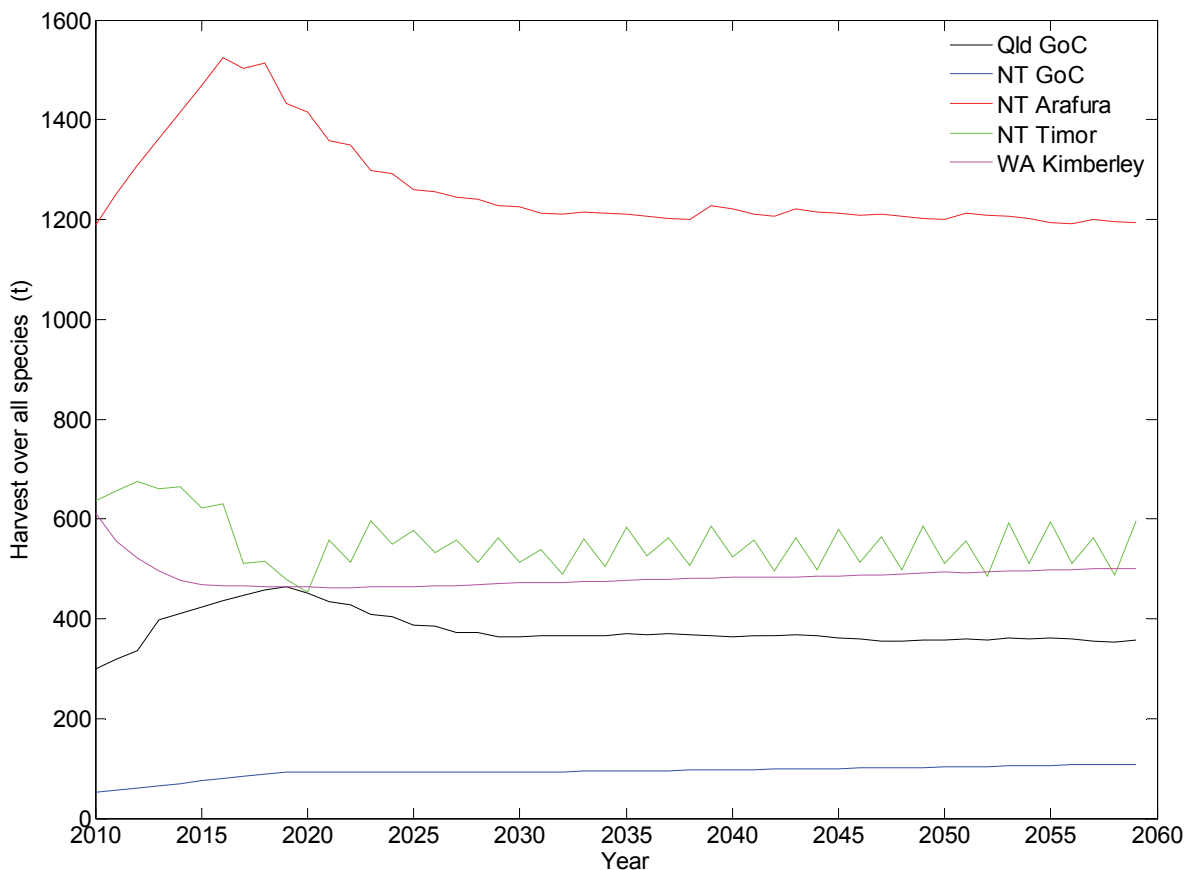


Figure 25 Harvest for Scenario 4 (monitoring every two years), summed over all species and averaged over 1000 simulations.
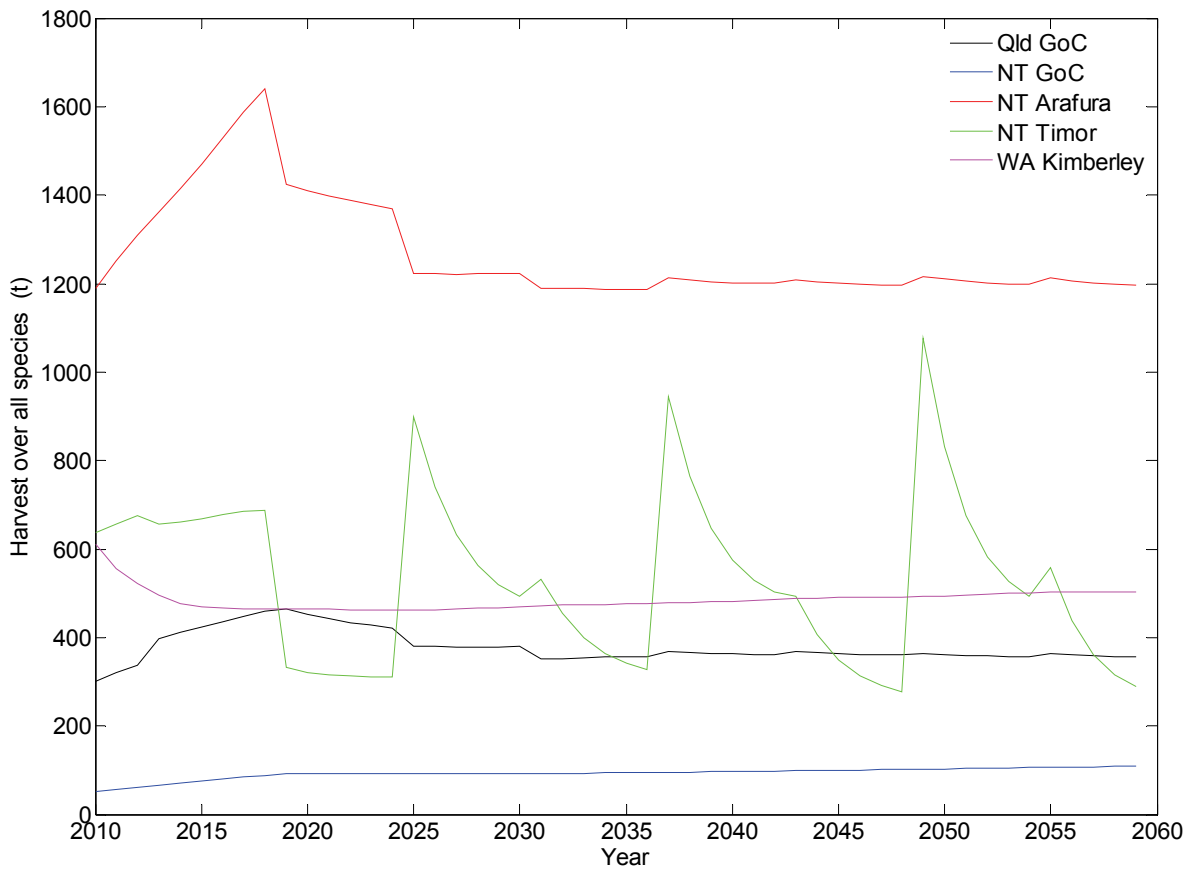
Figure 26 Harvest for Scenario 5 (monitoring every six years), summed over all species and averaged over 1000 simulations.
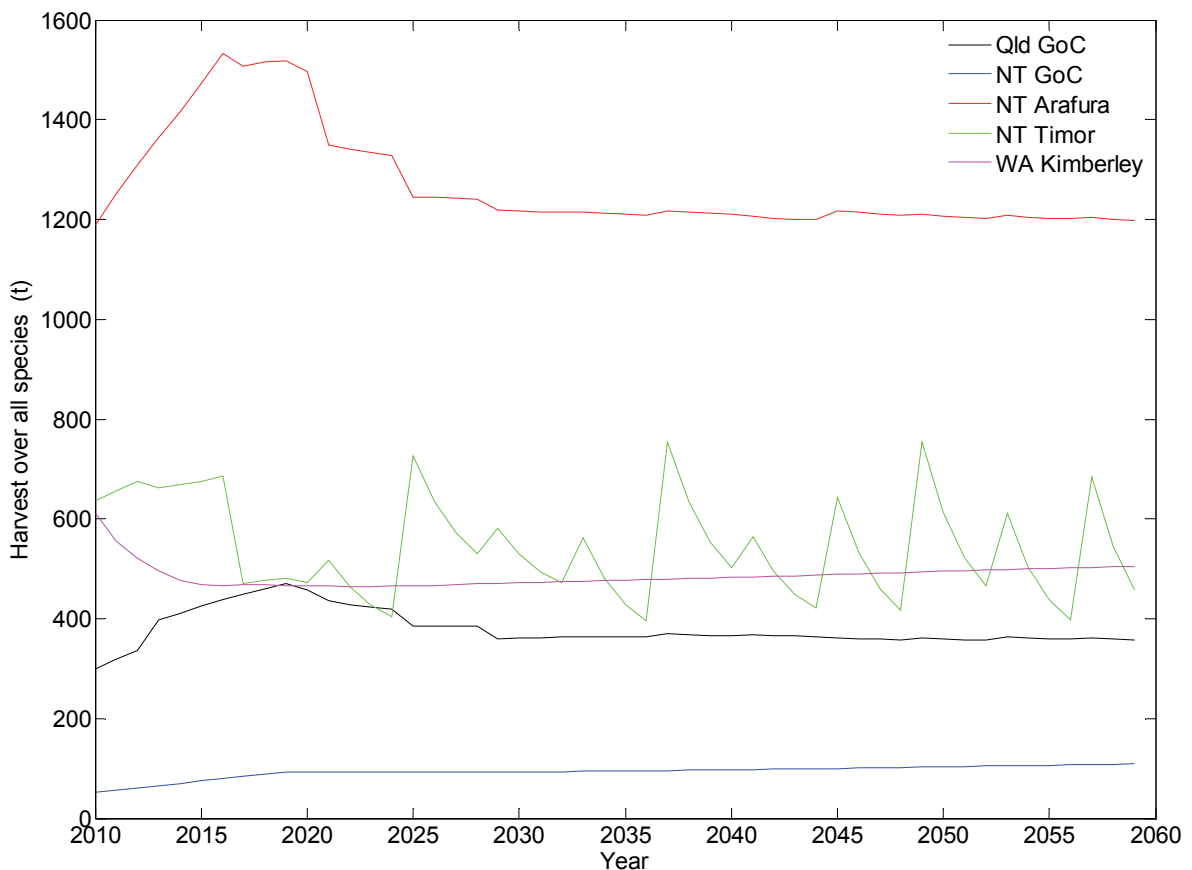


Figure 27 Harvest for Scenario 6 (100 monitoring days), summed over all species and averaged over 1000 simulations.

Figure 28 Harvest for Scenario 7 (constant TAC in Qld and NT, no monitoring), summed over all species and averaged over 1000 simulations.



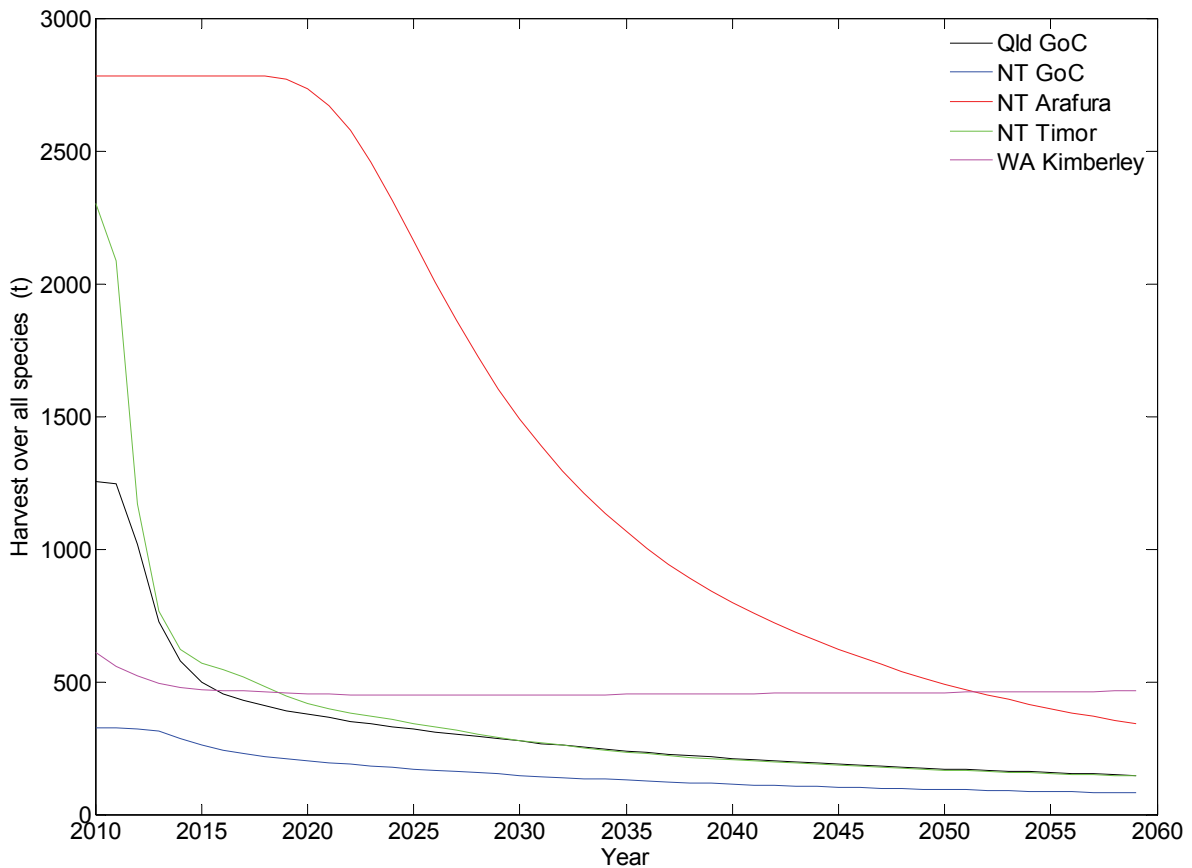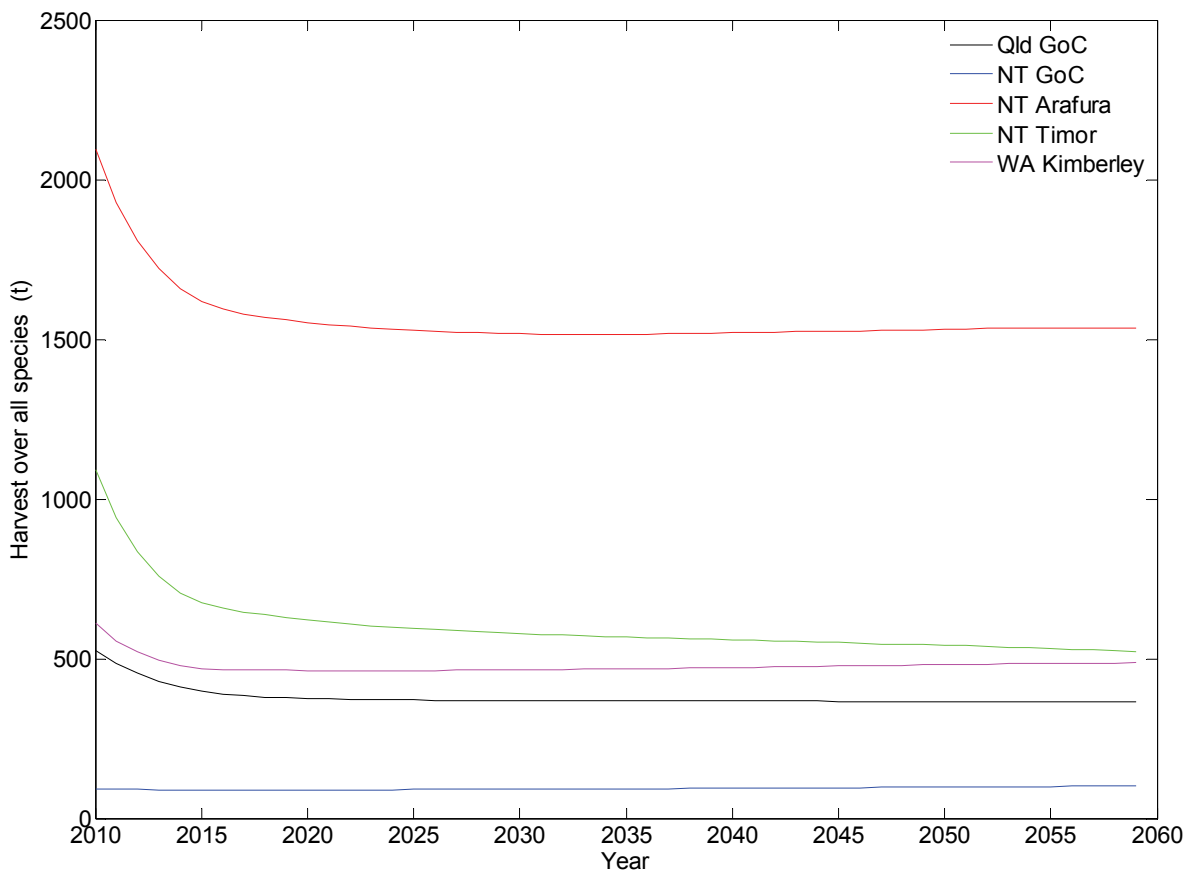Figure 29 Harvest for Scenario 8 (constant effort, no monitoring), summed over all species and averaged over 1000 simulations.

Figure 30 Harvest (total over all species) for a single typical simulation run for Scenario 1 (base case).



Figure 31 Harvest (total over all species) for a single typical simulation run for Scenario 6 (100 monitoring days instead of 50).

## 7.5 Monitoring program using commercial vessels

The Kimberley fishery in Western Australia (Figure 1, page 10) has established a monitoring program for tropical snappers (specifically for *P. multidens* and *L. sebae*). The program runs every four years. On board, scientific observers record all catches landed from the surveys (fish species number and weight, lengths and otoliths for aging). The contracted monitoring vessels require at least two observers per boat. The Department of Fisheries WA was strongly in favour of doing comprehensive age structured monitoring every four years, as against a rotational scheme which would sample a different subregion each year.

This project adopted the WA approach for monitoring and tested this in management strategy evaluation (MSE). Project investigators discussed the option that better estimation of relative year-class strength (age structures) could be possible if smaller annual surveys were conducted; analysis of data would still be every four years. However, the authors felt it was better to ensure consistency and rigour in detailed sampling every four years. Smaller, less controlled sampling may result in different locations being sampled in different years. From the analyses and modelling, and considering total harvest tonnages, the following candidate indicator species are suggested in order of priority:

1. WA Kimberley waters: *L. sebae*, *P. multidens* and *L. malabaricus*.
2. Timor Reef waters: *P. multidens*, *L. malabaricus* and *L. sebae*.
3. Arafura Sea waters: *L. malabaricus*, *P. multidens*, *L. sebae* and *L. erythropterus.*
4. Gulf of Carpentaria waters: *L. erythropterus, L. malabaricus*, *L. sebae* and *L. argentimaculatus*; *L. sebae* is included despite small catch sizes because it is a high-priced fish and its catch rates have declined (see section 7.1 and Figure 6).

*L. johnii* data did not provide sufficient power to develop critical fishery indicators. Near shore sampling would be required for this species. Specific consideration for *L. argentimaculatus* sampling sites may also be required for the Gulf of Carpentaria.

Project staff agreed that for monitoring of long-lived fish, age structures were required no more than every four years. As shown in Commonwealth SSESF fisheries, tier 3 equilibrium $F$ estimates from long-lived fish age data alone can be unresponsive in detecting sizable short-term (less than 5–10 years) changes in fishing mortality (Wayte, 2009). Substantial amounts of inertia can exist in age structures of long lived fish. The age at 50% recruitment for tropical snappers appears to be around six or seven years for all species and fishing methods (Table 10). Given the likely inability of age data to detect short-term changes in fishing pressure, this project has also tested fishery-standardised catch rates in biennial management procedures, with a comprehensive combined analysis including monitoring catch rate and age data conducted every four years. Accurate estimation of fish age structures is expensive, but can be funded every four years.

This report does not detail specific monitoring procedures. The WA Kimberley sampling design (three areas ∗ three nested sites; ≈ 450 *L. sebae* and *P. multidens* aged), field and laboratory procedures have already been outlined and used. Existing monitoring protocols detail field and laboratory procedures in Queensland (http://www.dpi.qld.gov.au/28_10737.htm). This operational detail is not replicated here, but important considerations for the structured fishing surveys are emphasised:

1. Survey structured fishing locations every four years: It is critical for each sector's design to have randomly selected sampling units (trawling, trap or line) with spatial and temporal replication. If too few replicates are sampled it can be difficult to separate nuisance

confounding sources. The objectives for monitoring are to estimate the change in population abundances and age structures (to estimate fishing mortalities), so it is best to use the same sites for each survey (Skalski, 1990). Alternatively, a serially rotating panel design with a mix of fixed and random sites could be considered (Brown, 2001; Skalski, 1990). Over time more sites would be monitored ensuring good geographical and temporal knowledge.

2. Sample sizes: Results suggest at least 50 days of observer coverage in each region every four years. These monitoring days should be stratified by location, and preferably each quadrennial monitoring episode should be conducted in the same months of the year. For trawl surveys, 50 days equated to about 100 independent trawl shots. More trawl shots may be required if high frequency of zero catches occur for the prime target species. We recommend replicating 50 trawls shots twice within the spawning months in each region (about 2 months apart to minimise difference in fish growth between age samples). Trawl swept area variables should be recorded to standardise catch rates as fish densities. Short ½ hour trawl shots are recommended to increase survey coverage. For fish age frequencies, a minimum of 500 fish should be aged. No more than 50 should be taken from any one trawl shot. If otoliths from more than 1000 fish of any one species are collected, they can be subsampled by scientists so that no more than 1000 fish of each species have to be aged.

3. Observer sampling: It is important to recognise that observer monitoring may force changes to the commercial fishing procedures that the vessels would otherwise employ. Care must be taken to ensure appropriate sampling sites, design of onboard data collection and safety. Observers need to work efficiently with vessel crew. Two observers will be required to record counts and measure fish caught, obtain otolith bone samples and record sampling effort. Consistent sampling procedures are required to ensure scientific rigour and to work smoothly within the fishing process.

4. Costs: Investment in monitoring will need to be planned and budgeted over the four year cycle. The following are indicative commercial observer costs for monitoring as calculated by Fisheries Queensland (M. Dunning and S. Helmke pers. comm.):
   - Processing and aging of otoliths at $16 per otolith,
   - Observer salary at $600 per person day,
   - Flights and travel $700 per person trip,
   - Allowances $250 per person day, and
   - Equipment at $1000.

Industry vessel and salary, and stock assessment costs were not estimated.

# 8   BENEFITS AND ADOPTION

The beneficiaries of the research are industry and management:

1. Northern Australian commercial snapper trawl, line and trap fisheries between the Kimberley and Cape York
2. The Northern Australian Fisheries Committee (NAFC)
3. The Department of Employment, Economic Development and Innovation (DEEDI), Queensland
4. The Department of Resources—Fisheries, Northern Territory
5. The Department of Fisheries, Western Australia
6. The Australian Fisheries Management Authority (AFMA)
7. The Department of Agriculture, Fisheries and Forestry (DAFF), Australian Government.

The research provided a number of benefits and updated our understanding of tropical snapper stocks. The collations of data and analyses have:

1. Detailed specifications for a structured observer-industry monitoring program, including a rough guide to the cost to industry in terms of number of observer days and number of otoliths to analyse. This will enable industry to invest data, prove fishery production and contribute to co-management of the fisheries across jurisdictions.
2. Detailed a pilot empirical management procedure, with reference points and control rules, based on observer-industry monitoring of fish catch rates and age structures.
3. Developed a graphical user interface modelling tool for unified and consistent monitoring, assessment and management of tropical snappers across jurisdictions. The tool also provides a framework for future modelling of the stocks.
4. Improved harvest recommendations for tropical snappers.
5. Provided detail to complete the Northern Australia red snapper Harvest Strategy Framework.
6. Provided opportunity for increased industry confidence and possible co-management of the fisheries through an open and transparent process.
7. Enhanced multi-agency collaborations.
8. Provided a centralised data hub for historic tropical snapper data for future research and assessment.

It was difficult to quantify the benefits of the research in terms of price or value of the yield. However, from this science the adoption of unified monitoring and management will result in:

1. Reduced management, observer and research costs across jurisdictions.
2. An opportunity for operators to improve planning and profitability of their fishing operations through understanding of the future catch rates that can be expected and maintenance of higher catch rates than would otherwise occur.
3. Potential progression of the Queensland Gulf of Carpentaria fishery from a developmental fishery to a licensed fishery.
4. Improved recognition of fishery sustainability for domestic and overseas marketing.

In terms of direct contact and adoption of the research, each jurisdiction's fishery managers have been involved directly through discussions with project staff. A presentation of project outcomes has been delivered to key trawl industry members. Direct adoption will be post-project. The structure of future monitoring and management is dependent on the completion of the Northern

Australia red snapper Harvest Strategy Framework, industry acceptance, NAFC and each jurisdiction's endorsement.

The data, methods and modelling tools from this project were relevant to and support the ACIAR project FIS/2006/142 "Developing new assessment and policy frameworks for Indonesia's marine fisheries, including the control and management of illegal, unregulated and unreported (IUU) fishing". Direct linkage of the FRDC project to ACIAR was achieved through co-investigator Dr Cathy Dichmont. Dr Dichmont attended various project steering committee meetings, and reported on several occasions to the ACIAR project. This latter project was awaiting outcomes of this FRDC project so that it can report on the results. The ACIAR project will then engage (as required) with various agencies regarding the next steps recommended.

As reported during the FRDC project, the ACIAR work made limited progress sourcing further reliable harvest data from a number of important Indonesian sectors. Conducting reliable stock assessment on Indonesian snappers may be unachievable in the medium term. The ACIAR project will benefit from FRDC 2009/037 with respect to data and MSE recommendations, and availability of the modelling tools. The monitoring and management procedures recommended for Australian waters would also have direct application in Indonesian. In the FRDC project, snapper movement to and from Indonesian waters was handled by including an extra component of fishing mortality on snapper populations in Australian waters. This fishing mortality was additional to that applied by fishers operating in Australian waters. Fishing mortality in Indonesia is believed to be higher and to apply to younger fish than in Australia because of Indonesia's higher human population and greater reliance on fishing to provide food, and fewer restrictions on gear and catch size. Modelling the Indonesian effect as an extra fishing mortality term avoided the need to specify both the snapper movement rate to Indonesia and the fishing mortality rate in Indonesia; it required only the combined effect of the two. Various values for the effect of Indonesian fishing currently can be tried, even though at present they cannot be verified from data; verification may be possible at some time in the future.

Australian stakeholders and managers will benefit from the knowledge that Indonesian fishing mortality can be accounted for in Australian research and management. Currently, the effects of Indonesian fishing on the Australian fisheries are highly uncertain, but it is possible to determine hypothetical levels of fish movement and Indonesian fishing mortality at which Australian fishery management would be seriously compromised.

The benefits and beneficiaries stated above were aligned with those identified in the original project application. This was accomplished through various project meetings between scientists, fishery managers and stakeholders, and progress against communication and extension plan.

## 9   FURTHER DEVELOPMENT

Research and other activities that should be undertaken to further develop tropical snapper research and management include the following:

***Disseminate outputs to fishery managers, the jurisdictions, NAFC and industry:*** Further discussions and presentations are required to promote adoption of monitoring and better management. Travel is required to extend project results to NAFC, industry members, SAGs and MACs late 2011.

***L. sebae in Northern Territory and Queensland waters:*** A consistent decline in catch rates of *L. sebae*, together with WA research (Newman and Dunk, 2002), indicates low production potential compared to the other five tropical snapper species. Further monitoring, biological and harvest strategy work is required to clarify sustainable fishing rates. This work should extend to include Queensland east coast waters, as stock status there is uncertain (Fisheries Queensland, 2010).

***Quantify fishing power increases:*** The effects of improvements in fishing gear and technology on logbook catch rates need to be quantified. Statistical models were developed, but the standardisations lacked this technological improvement data.

***More sophisticated catch curve analyses to inform management:*** Further development of the empirical technique for assessing population status from age structures is required. Significant amounts of inertia can exist in long lived fish age structures. Given the inability of equilibrium methods to detect short-term changes in fishing mortality, catch curve analyses that don't require assumptions of equilibrium (i.e., long-term constant fishing mortality rates and recruitment) need to be included. The assumption of constant recruitment can be overcome by using longitudinal catch curves, which allow for variable recruitment from year to year and track each year-class or cohort longitudinally from one monitoring episode to the next. Overcoming the assumption of constant long-term fishing mortality requires a technique of catch-curve analysis that estimates only recent fishing mortality rates. Further analyses are required to explore the feasibility of these approaches when monitoring is conducted every four years. The project staff appreciated that both catch rates and age structure are subject to large variation.

Accurate estimation of fish age structures from sectioning and reading otoliths is expensive, although less costly than the process of collecting the otoliths. Use of otolith weights instead of ring counts could be explored.

***Important gaps in data:*** The most important gap that could be filled in existing data is a detailed understanding of the schooling behaviour of tropical snappers. For example, do they school by age group in certain depths or at certain times of the year or do species school in mixed age groups? We expect future monitoring to provide major updates. After the first round of monitoring surveys, it should be beneficial to revisit some of the analyses conducted during this project. It is critical that the monitoring surveys include detailed shot-by-shot information on location, habitat (at least in terms of depth) and age structure.

There is also a need to better quantify the stock structure of tropical snappers across Northern Australia. The need here is to define the level of mixing between both adult and juvenile

populations (as well as their distribution). Similar studies on threadfin salmon have recently been completed across Northern Australia (Welch et al., 2010).

It is generally the case in fisheries stock assessment that the item highest on the wish list of assessment scientists is accurate data from very early in the history of the fishery. In most cases, the opportunity to collect such data has passed. For the tropical snapper fishery, however, the next best thing is collection of data while the fishery is recovering after the cessation of foreign fishing and filled proportions of Queensland and Northern Territory TACs are still low. In this regard, we expect data from the first monitoring episode (possibly 2012) to be very useful to future stock assessment.

Data on *L. johnii* are currently insufficient for much analysis, and should be augmented by inshore surveys if this species is considered important to management agencies.

***Further development of modelling tool:*** The modelling tool should be further developed to assess alternate management procedures, including proposed Government marine zoning and any displacement of fishing effort. Inshore fishing grounds and their data should be included in the tool. This will enable management options to be tested on inshore juvenile and offshore adult life cycles. The model could also be expanded to include the Queensland east coast and Western Australian Pilbara waters. The Bayesian hierarchical nature of the model has provided a more accurate view of the stocks as a whole than an analysis of each species and jurisdiction separately. This tool could be further adapted in a larger study for other important tropical fish families, such as mackerel, threadfin salmon and barramundi. The flexible tool structure will allow easy development for environmental, oceanographic or climatic effects to be quantified. More sensitivity analyses on data and assumptions are required, which was beyond this one-year project.

***Data management after project:*** The project collated tropical snapper data across jurisdictions and agencies. Appendix 7—Table 27 outlined the metadata on page 104. The data were stored in MS Access and Excel files. The files are located under DEEDI secure network directories for stock assessment. Network backup copies are run daily. Each agency has been provided copies of their fisheries data. For future research use, access must be granted by the relevant agencies.

## 10  PLANNED OUTCOMES

The project outputs provided the framework to improve the monitoring, management and sustainable use of tropical snapper resources. The outputs will contribute to long term profitability and marketability of the fisheries, plus reduce management costs.

The project delivered specifications to implement a Northern Australian harvest strategy for tropical snappers. The project outputs, together with a future monitoring and harvest strategy, will provide greater certainty for fisheries managers and industry through establishing an open and transparent process to manage the fisheries. The project contributed to a multi-jurisdictional management framework. The research enhanced multi-agency collaborations by developing numerical techniques for collaborative assessments and analysis of monitoring data.

The project delivered on NAFC's priority for tropical snapper research.

The project provided further evidence for a combined monitoring/assessment/management approach for shared fish stocks across Northern Australia. It showed the strong need to share financial resources in order to effectively monitor and manage long-lived tropical snappers. Further, the project provided holistic methods for dynamically setting TACs or TAEs by regions, which could also be applied to other northern fish stocks.

The project better informed stakeholders and managers about their jurisdictional and sectoral linkages, and the important need to accurately monitor long-lived tropical snappers.

The project examined monitoring options for golden snapper that will support current NT research on this species.

The HSF and monitoring outcomes from this project will be relevant to and support the ACIAR project FIS/2006/142 "Developing new assessment and policy frameworks for Indonesia's marine fisheries, including the control and management of illegal, unregulated and unreported (IUU) fishing".

Project results were communicated through meetings with fishery managers and Queensland Gulf of Carpentaria and NT fish trawl operators. Fisheries Queensland and NT fishery managers have actioned discussions and planning for a four year monitoring cycle. Operators agreed in concept to gather the necessary data to make assessments more robust. It was considered desirable to match the four-year monitoring cycle between the jurisdictions; preferably starting 2012.

Project results contributed further to Goldband snapper stock assessments conducted by NT government and Dr Carl Walters in July 2011; their assessment and report outcomes are pending.

This project has described data, methods, analyses and empirical management measures for tropical snappers. It has also highlighted how to apply quantitative methods in setting sustainable harvest and fishing effort. When stock dynamics are uncertain, precautionary quota and effort levels are recommended. The results demonstrate the technical advantage of using monitoring data within empirical management rules. The adaptive capacity of the data and rules significantly improves management over current constant TAC. The work contained in this report has national significance for assessment and management of target species across northern Australia.

Data analyses indicated that critical indicators of fishery performance can be developed with sufficient statistical power (objective 1). Results from sections 7.1and 7.2 indicated data have intrinsically large variances. Simulation modelling (objective 2) further showed that sufficient effective sample sizes were required to overcome these variances to understand the accuracy and use of age structured and catch rate information (results sections 7.3 and 7.4). To develop sound monitoring (objective 3), strategies are required to ensure vessel, gear, spatial and seasonal variance effects are minimised (results section 7.5). As the use of finfish trawl sampling is likely, recording of shot-by-shot fine scale data with swept area effort variables is recommended. Further recommendations and conclusions from the project were:

*Catch rate data:* Catch rates have intrinsically large variances. To minimise variance, data must be recorded at fine scale (e.g., location and effort for each trawl, trap or line catch unit). Commercial logbooks should be reviewed and made consistent across jurisdictions. Catch monitoring and analyses require strategies to reduce vessel, gear, spatial and seasonal variances. Two-component statistical models should be used to correctly standardise mean catch rates for effective use as critical indicators in management. These models should include finer spatial scales to account for changes in fishing locations and targeting (as per Carruthers et al., 2011)

*Age data:* Aging protocols need to be standardised between agencies to minimise errors and bias. Ring-count data should be standardised to age groups (cohorts). Cohort-based analysis of age frequencies could be employed to estimate fishing mortality for management.

*Monitoring program:* Structured fishing locations are required every four years. It is critical for each sector's design to have randomly selected sampling units (trawling, trap or line) with spatial and temporal replication. If too few replicates are sampled, it can be difficult to separate confounding sources. The objectives for monitoring are to estimate the change in population abundances and age structures, so it is best to use the same general areas for quadrennial sampling. Spatial coverage of the stocks (including both heavily and lightly fished areas) is required, and must have an unbiased pattern. Accurate observer monitoring of tropical snapper catch rates requires a minimum number of 50 fishing days to be sampled per sector. As the most likely candidate survey methodology will employ the use of finfish trawl apparatus, ongoing communication with this sector is essential. Management and assessment staff need to promote the harvest strategy framework and information required to improve assessment of the stocks.

Not more than 50 fish of one species in a single shot are required to be aged for acceptable precision, because achievable effective sample sizes (i.e., equivalent numbers of individual fish sampled completely independently from a whole regional population) are quite low (perhaps 20 or

less). Aging of more than 50 fish will not increase the precision of estimation of age structures. If not all fish of a given species in a shot are to be aged, the selection of fish for aging must be either completely random or randomly stratified by length.

Total allowable catch or effort (TAC or TAE) can be set every four years, after each monitoring episode, in order to maintain sustainability of the fisheries. More frequent setting is not necessary, although if catch rates fall to 70% or less of the reference value after two years, TAC or TAE can be reduced by 30% to avoid the need for more severe changes later.

***Modelling tool:*** The modelling tool should be used and maintained frequently for testing monitoring, assessment and management procedures. The model is operated by a user-friendly graphical user interface. The Bayesian hierarchical nature of the model provided a more accurate view of the status of the stocks as a whole than analysing each species and jurisdiction separately.

Cross-jurisdictional monitoring and management is a priority. If management agencies do not adopt new monitoring and harvest strategies, precautionary levels of quota and effort are needed. TAC by species can be critically evaluated using the new quantitative modelling tool.

***Collation of data:*** The databases from this project should be used to store new data in future assessments.

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## 13  APPENDIX 1: INTELLECTUAL PROPERTY

A software tool for management strategy evaluation was developed as part of this project. An executable version will be distributed to fishery management agencies in Queensland, Northern Territory and Western Australia.

The research is for the public domain. The report and any resulting manuscripts are intended for wide dissemination and promotion. All data and statistics presented conform to confidentiality arrangements.

## 14  APPENDIX 2: STAFF

The following table lists project staff involved in the project.

| Name | Government organisation | Funding |
|------|------------------------|---------|
| Begg, Gavin | ABARES, Australian | FRDC and in-kind |
| Chambers, Mark | ABARES, Australian | FRDC and in-kind |
| Dichmont, Cathy | CSIRO, Australian | In-kind |
| Kienzle, Marco | CSIRO, Australian | FRDC |
| Miller, Margaret | CSIRO, Australian | FRDC |
| Leigh, George | DEEDI, Queensland | FRDC and in-kind |
| O'Neill, Michael | DEEDI, Queensland | FRDC and in-kind |
| Buckworth, Rik | DoR-Fisheries, Northern Territory | FRDC and in-kind |
| Lee, HockSeng | DoR-Fisheries, Northern Territory | In-kind |
| Martin, Julie | DoR-Fisheries, Northern Territory | FRDC and in-kind |
| Newman, Steve | Fisheries, Western Australia | FRDC and in-kind |

# 15  APPENDIX 3: CODE, RESULTS AND DIAGNOSTICS FOR CATCH RATES

## 15.1  Trawl catches from Eastern Gulf of Carpentaria waters, Queensland

Table 16 Example GenStat code used to analyse Qld trawl snapper catches.

```
"***** Conditional Binomial/log-Normal Model *****"
"Lutjanus malabaricus etc; 14.6% zeros, varies by year but skewed residuals "

calculate otherslog=log(lery+lseb+larg+ljon+lrus+hus+unspec+dper+1) "add minor species together"

GLMM [PRINT=model,monitor,components,vcovariance,means,backmeans,effects,wald; DISTRIBUTION=binomial;\
 LINK=logit; DISPERSION=*; FIXED=year+lunar+lunar_adv+otherslog; RANDOM=boat+month+grid+grid.site;\
 CONSTANT=estimate; FACT=9; PSE=estimates; MAXCYCLE=20; FMETHOD=all; CADJUST=mean]\
 y=problmal; means=logitpred;BACKMEANS=binyear;varmeans=logitvar; NBINOMIAL=1

vdisplay[print=deviance]

calculate pderiv=exp(logitpred[1])/(1+exp(logitpred[1]))**2
vtable table=pderiv; variate=pderiv2
vtable table=binyear[1]; variate=binyear2
calculate logitvar2=diagonal(logitvar[1])
calculate binyearse=abs(pderiv2)*sqrt(logitvar2)

RESTRICT lmal; lmal.NE.0

VCOMPONENTS [FIXED=year+lunar+lunar_adv+otherslog;\
 FACTORIAL=2] RANDOM=boat+month+grid+grid.site;  INITIAL=1;CONSTRAINTS=none
REML [PRINT=model,components,effects,vcovariance,deviance,waldTests,\
covariancemodel,means; PSE=estimates; MVINCLUDE=*; method=ai;] loglmal

vplot pen=30

vkeep [SIGMA2=ems]
vpredict [print=pred,se; PRED=LnormYear; SE=LnormYearSE] year
vtable table=LnormYear; variate=lnormyear
vtable table=LnormYearSE; variate=lnormyearse

TABULATE [PRINT=means; CLASSIFICATION=year; MARGINS=no] lmal; means=lmalcpue2t
vtable table=lmalcpue2t; variate=lmalcpue2var

RESTRICT lmal "(unrestrict)"

" Method 2 for E(catch) with lognormal confidence intervals; backtransform + bias correct predictions to kg "
"combine predictors on log scale and back transform to kg"

calculate BCBTLnormYear=exp(lnormyear+ems/2) "bias corrected back transformed non-zero log analysis; by adding half variance"
calculate BinLnormYear=binyear2*BCBTLnormYear "E(catch) = P(catch) * E(catch | catch>0)"
calculate logp=log(binyear2)
calculate varlogp=(binyearse/binyear2)**2
calculate cilog=sqrt(varlogp+lnormyearse**2)*1.96
calculate selog=sqrt(varlogp+lnormyearse**2)
calculate pred = exp(logp + lnormyear + ems/2) "E(catch) as above"
calculate pred_lowci = exp(logp + lnormyear + ems/2 - cilog) "lower 95% CI"
calculate pred_upci = exp(logp + lnormyear + ems/2 + cilog) "upper 95% CI"
calculate pred_lowci_nz = exp(lnormyear + ems/2 - lnormyearse*1.96) "lower 95% CI"
calculate pred_upci_nz = exp(lnormyear + ems/2 + lnormyearse*1.96) "upper 95% CI"
calculate pred_nz=BCBTLnormYear

TABULATE [PRINT=means; CLASSIFICATION=year; MARGINS=no] lmal; means=lmalnom
vtable table=lmalnom; variate=lmalnomvar
TABULATE [PRINT=means; CLASSIFICATION=year; MARGINS=no] problmal; means=lmalpnom
vtable table=lmalpnom; variate=lmalpnomvar

"print results for plotting in MATLAB"
print binyear2,binyearse,logitvar2,pred_nz,pred_lowci_nz,pred_upci_nz,pred,pred_lowci,pred_upci,\

lmalnomvar,lmalpnomvar,lmalcpue2var,selog; decimals=6
```

# loglmal

## Histogram of residuals



## Fitted-value plot
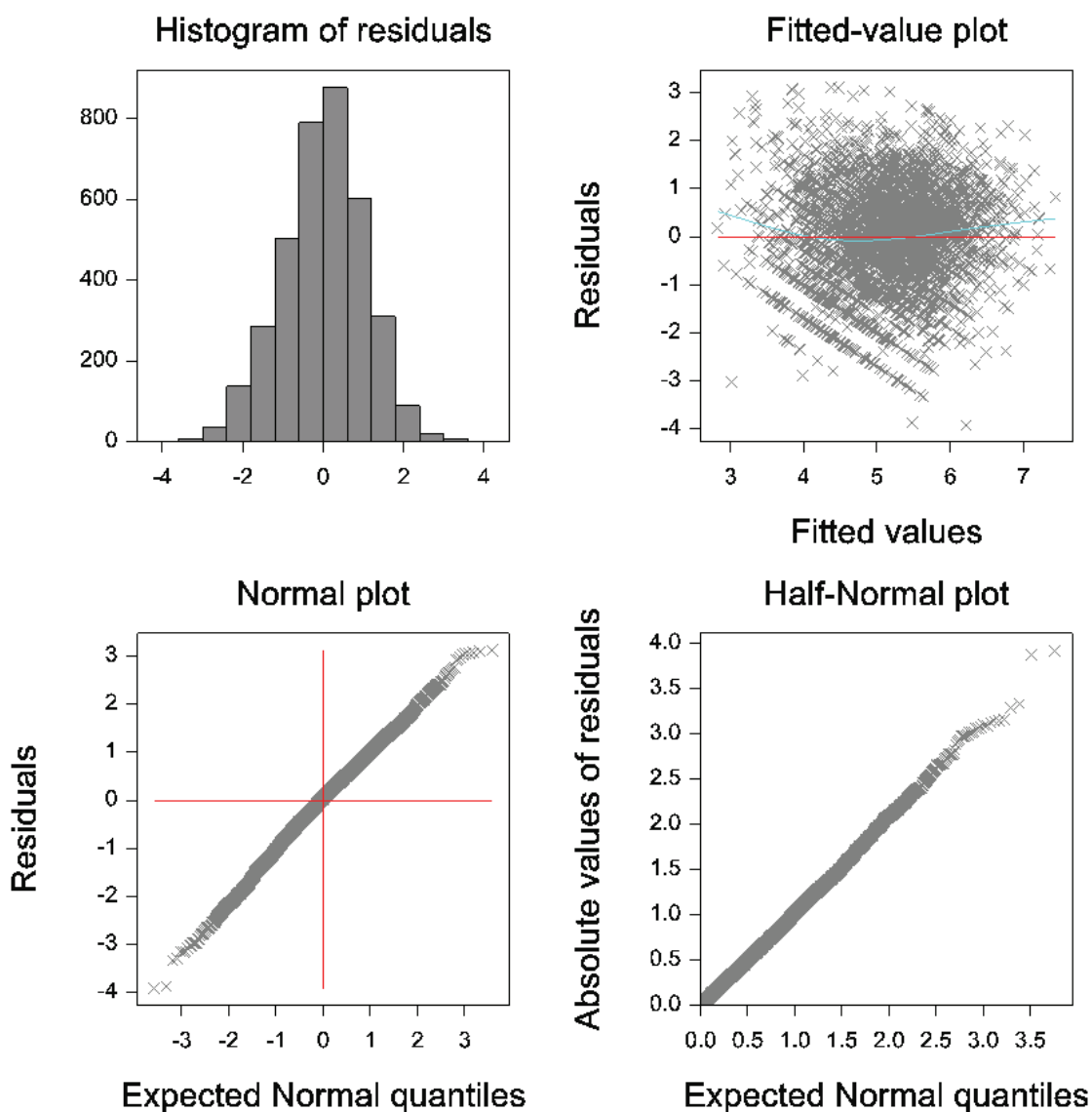


## Normal plot



## Half-Normal plot



Figure 32 Standardised residuals from the REML analysis of *L. malabaricus* daily catches by vessel and grid-site. The use of log-normal error was appropriate with no pattern in standardised residuals and linear normality plots. This result was the same for other species analysed.

Table 17 Summary of conditional analyses of trawl harvests (kg) taken per vessel grid-site day from eastern Gulf of Carpentaria waters, Queensland. Summary includes $F$ statistics and probabilities of no significance for fixed model terms; standard errors are shown within parentheses.

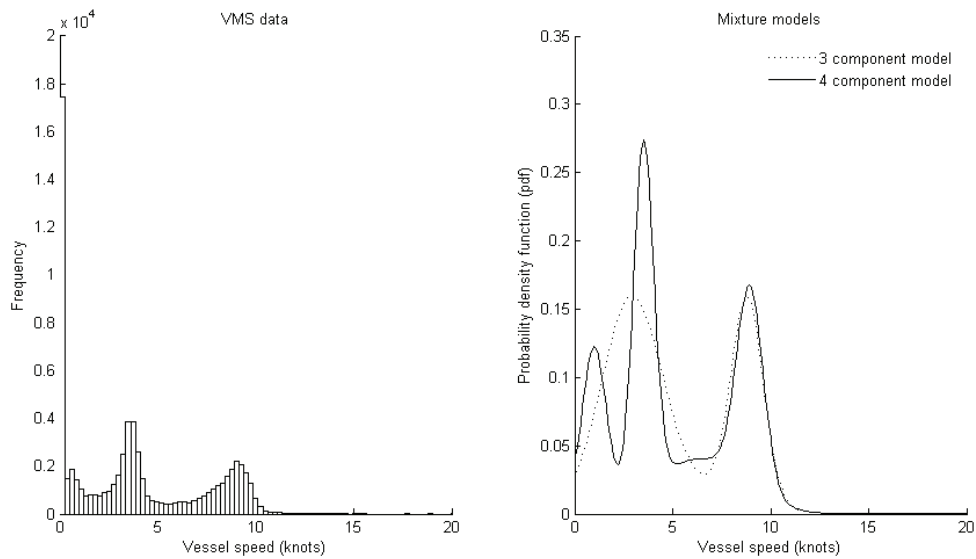| Conditional models | *L. erythropterus* | *L. malabaricus* | *L. sebae* | *L. johnii* | *L. argentimaculatus* |
|---|---|---|---|---|---|
| **Binomial GLMM** | | | | | |
| Summary of analysis | | | | | |
| % zero catches | 9 | 14.6 | 67.7 | 83.5 | 53.3 |
| Deviance: -2*LL | 16712.17 | 16309.24 | 12396.86 | 14188.6 | 11369.54 |
| Residual d.f. | 4275 | 4274 | 4274 | 4276 | 4274 |
| Dispersion | 0.941 (0.0205) | 0.815 (0.0184) | 0.91 (0.0206) | 0.821 (0.0188) | 1.01 (0.023) |
| Fixed terms | | | | | |
| Fishing year | 10.46, <0.001 | 4.35, <0.001 | 33.64, <0.001 | 4.62, <0.001 | 6.35, <0.001 |
| Luminance | 0.38, 0.538 | 4.59, 0.032 | 0.12, 0.733 | 0.63, 0.428 | 9.09, 0.003 |
| Luminance + 7 days | 0.06, 0.799 | 0.82, 0.364 | 0.68, 0.408 | 0.44, 0.508 | 0.23, 0.634 |
| Log other Lutjanidae | 2.7, 0.101 | 0, 0.969 | 104.24, <0.001 | – | 273.67, <0.001 |
| Random terms - Variance components | | | | | |
| Vessel | 0.1678 (0.1637) | 1.0557 (0.8846) | 0.1489 (0.1431) | – | 0.028 (0.034) |
| Month | 0.1628 (0.0905) | 0.2559 (0.126) | 0.1244 (0.0615) | 0.0926 (0.0509) | 0.067 (0.036) |
| Grid | 0.4273 (0.1441) | 2.1512 (0.5085) | 0.575 (0.1607) | 0.5396 (0.1518) | 0.294 (0.086) |
| Grid.site | - | 0.3026 (0.0932) | 0.153 (0.0502) | 0.3452 (0.0821) | 0.063 (0.037) |
| **Linear mixed model** (REML) | | | | | |
| Summary of analysis | | | | | |
| Deviance: -2*LL | 5012.72 | 4205.64 | 719.35 | 1155.31 | 3138.45 |
| Residual d.f. | 3889 | 3648 | 1365 | 691 | 1984 |
| Residual variance | 1.232 (0.03) | 1.082 (0.027) | 0.535 (0.0231) | 1.552 (0.102) | 1.601 (0.055) |
| Fixed terms | | | | | |
| Fishing year | 15.8, <0.001 | 14.46, <0.001 | 14.17, <0.001 | 4.46, <0.001 | 10.96, <0.001 |
| Luminance | 1.51, 0.219 | 0.02, 0.879 | 1.19, 0.276 | 0, 0.995 | 0.41, 0.52 |
| Luminance + 7 days | 2.63, 0.105 | 0.01, 0.934 | 0.65, 0.42 | 1.06, 0.305 | 3.25, 0.072 |
| Log other Lutjanidae | 725.61, <0.001 | 657.71, <0.001 | 117.57, <0.001 | 85.92, <0.001 | 380.72, <0.001 |
| Random terms | | | | | |
| Vessel | 0.031 (0.029) | 0.031 (0.028) | 0.1674 (0.1434) | 0.223 (0.215) | 0.069 (0.068) |
| Month | 0.009 (0.006) | 0.038 (0.018) | 0.0278 (0.0148) | -0.007 (0.011) | 0.005 (0.006) |
| Grid | 0.072 (0.025) | 0.268 (0.067) | 0.025 (0.0139) | 0.506 (0.148) | 0.255 (0.075) |
| Grid.site | 0.062 (0.016) | 0.013 (0.009) | 0.0407 (0.0155) | 0.078 (0.067) | 0.059 (0.027) |

Figure 33 Histogram of VMS calculated vessel speeds and Gaussian mixtures used to identify trawling locations in east GoC waters, Queensland.
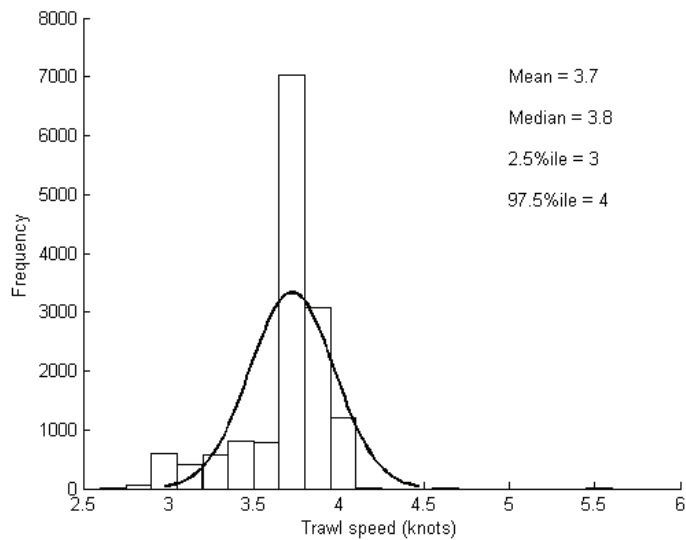


Figure 34 Histogram and normal density of trawl speeds logged by finfish trawl vessels in Northern Territory waters.
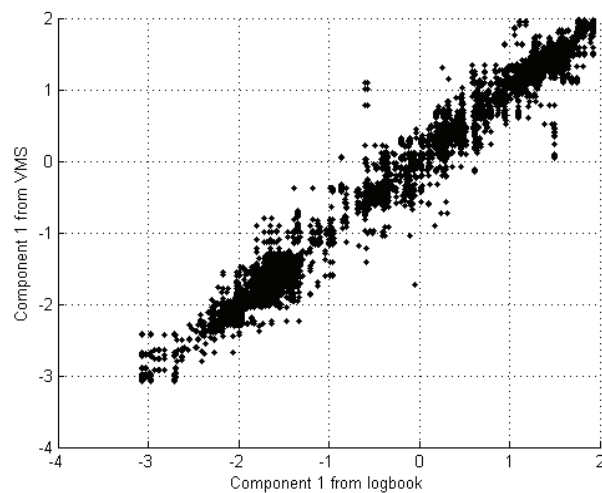


Figure 35 Comparison of logbook and VMS fishing locations using 1st principal component scores. Fitted slope was 0.99.

## 15.2 Catch rate analysis for Moses snapper, Queensland

Project scientists from Queensland DEEDI participated in the FRDC 2011 TRF project "Using innovative techniques to analyse trends in abundance for non-target species". In fisheries controlled by quotas there remain many species which are taken as by-product and a need has been expressed by AFMA for some form of assessment of these species. Some of these species while not direct targeted still contribute significant value to the total catch and so are of interest and concern to Industry bodies. ComFRAB noted that there is now an increased emphasis on the management of by-product and bycatch species, and the need for information on trends in abundance has been identified as a strategic research and management issue for Australian Government fisheries.

Under the TRF project objective, "investigate analysis methods capable of providing trend in abundance estimates for byproduct and bycatch species", *Lutjanus russellii* from eastern Queensland Gulf of Carpentaria waters was analysed as an example case study. Different statistical methods were explored during a two day workshop in March 2011. In summary:

- Poisson and two-stage models gave similar CPUE trends.
- It was important to identify and include zero catches.
- For this species, inconsistent catch reporting may be a problem before 2005.
- We don't believe that fish abundance really varied this much for a relatively long-lived species (maximum age ≈ 20 years); must be subject to very large sampling error.
- It makes a difference whether catch of "other" species is included.

Catch rates of main target species have fallen in recent years. Possibly the catch of target species is not a consistent indicator of effort applied to this by-product species. This may also be a problem in other fisheries, in that major target species catch rates may be down but by-product or by-catch species are not.
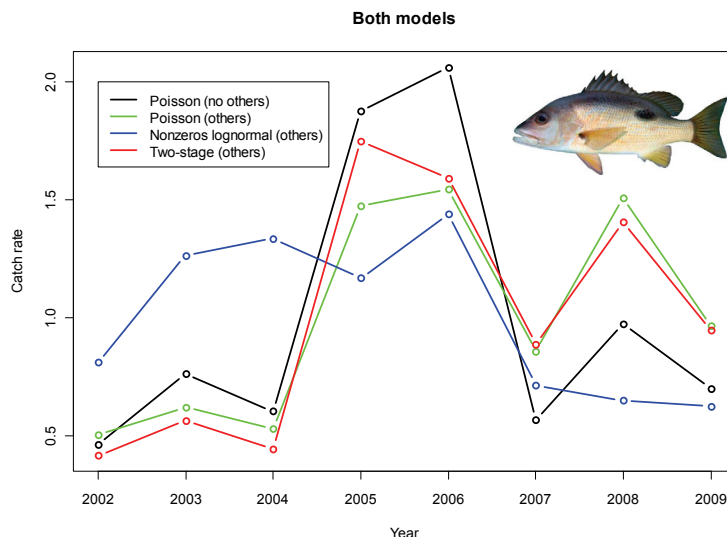


Figure 36 Moses snapper (*Lutjanus russellii*) annual trawl catch rates from eastern Gulf of Carpentaria waters, Queensland. Catch rates were standardised and compared from four analyses; overall mean standardised catch rate = 1.

## 15.3 Trawl fish catches from Arafura Sea and west GoC waters, NT

Table 18 Example GenStat code used to analyse NT trawl snapper catches.

```
"***** Conditional Binomial/log-Normal Model *****"
"Lutjanus erythropterus; 12% zeros, varies by year but skewed residuals "

calculate tw=(((speed*1.852*1000)*hrs)*net)/1000 "~swept area effort"
calculate logtw=log(tw)

calculate logshark=log(shark+1)
calculate logmack=log(scomm+1)
calculate logother=log(other+1) "not target lutjanids"

GLMM [PRINT=model,monitor,components,vcovariance,means,backmeans,effects,wald; DISTRIBUTION=binomial;\
 LINK=logit; DISPERSION=*; FIXED=year*zone2+problem_trawls+logtw+\
logmack+logshark+logother; RANDOM=month+area;\
 CONSTANT=estimate; FACT=9; PSE=estimates; MAXCYCLE=20; FMETHOD=all; CADJUST=mean]\
 y=problery; means=logitpred;BACKMEANS=binyear;varmeans=logitvar; NBINOMIAL=1

vdisplay[print=deviance]

calculate pderiv=exp(logitpred[3])/(1+exp(logitpred[3]))**2
vtable table=pderiv; variate=pderiv2
vtable table=binyear[3]; variate=binyear2
calculate logitvar2=diagonal(logitvar[3])
calculate binyearse=abs(pderiv2)*sqrt(logitvar2)
print binyear2,binyearse

RESTRICT lery; lery.NE.0

VCOMPONENTS [FIXED= year*zone2+logtw+logother;\
 FACTORIAL=2] RANDOM=month+area;  INITIAL=1;CONSTRAINTS=none
REML [PRINT=model,components,effects,vcovariance,deviance,waldTests,\
covariancemodel,means; PSE=estimates; MVINCLUDE=*; method=ai;] loglery

vplot pen=30

vkeep [SIGMA2=ems]
vpredict [print=pred,se; PRED=LnormYear; SE=LnormYearSE] year,zone2
vtable table=LnormYear; variate=lnormyear
vtable table=LnormYearSE; variate=lnormyearse

calculate lerycpue2=lery/tw
TABULATE [PRINT=means; CLASSIFICATION=year,zone2; MARGINS=no] lerycpue2;  means=lerycpue2t
vtable table=lerycpue2t; variate=lerycpue2var

RESTRICT lery "(unrestrict)"

" Method 2 for E(catch) with lognormal confidence intervals; backtransform + bias correct predictions to kg "
calculate BCBTLnormYear=exp(lnormyear+ems/2) "bias corrected back transformed non-zero log analysis; simple bias corrected mean, by adding half variance"
calculate BinLnormYear=binyear2*BCBTLnormYear "E(catch) = P(catch) * E(catch | catch>0)"
calculate logp=log(binyear2)
calculate varlogp=(binyearse/binyear2)**2
calculate cilog=sqrt(varlogp+lnormyearse**2)*1.96
calculate selog=sqrt(varlogp+lnormyearse**2)
calculate pred = exp(logp + lnormyear + ems/2) "E(catch) as above"
calculate pred_lowci = exp(logp + lnormyear + ems/2 - cilog) "lower 95% CI"
calculate pred_upci = exp(logp + lnormyear + ems/2 + cilog) "upper 95% CI"
calculate pred_lowci_nz = exp(lnormyear + ems/2 - lnormyearse*1.96) "lower 95% CI"
calculate pred_upci_nz = exp(lnormyear + ems/2 + lnormyearse*1.96) "upper 95% CI"
calculate pred_nz=BCBTLnormYear

calculate lerycpue=lery/tw
TABULATE [PRINT=means; CLASSIFICATION=year,zone2; MARGINS=no] lerycpue; means=lerynom
vtable table=lerynom; variate=lerynomvar
TABULATE [PRINT=means,nobs; CLASSIFICATION=year,zone2; MARGINS=no] problery; means=lerypnom
vtable table=lerypnom; variate=lerypnomvar
"print results for plotting in MATLAB"
print binyear2,binyearse,pred_nz,pred_lowci_nz,pred_upci_nz,pred,pred_lowci,pred_upci,\
lerynomvar,lerypnomvar,lerycpue2var,selog; decimals=6
```
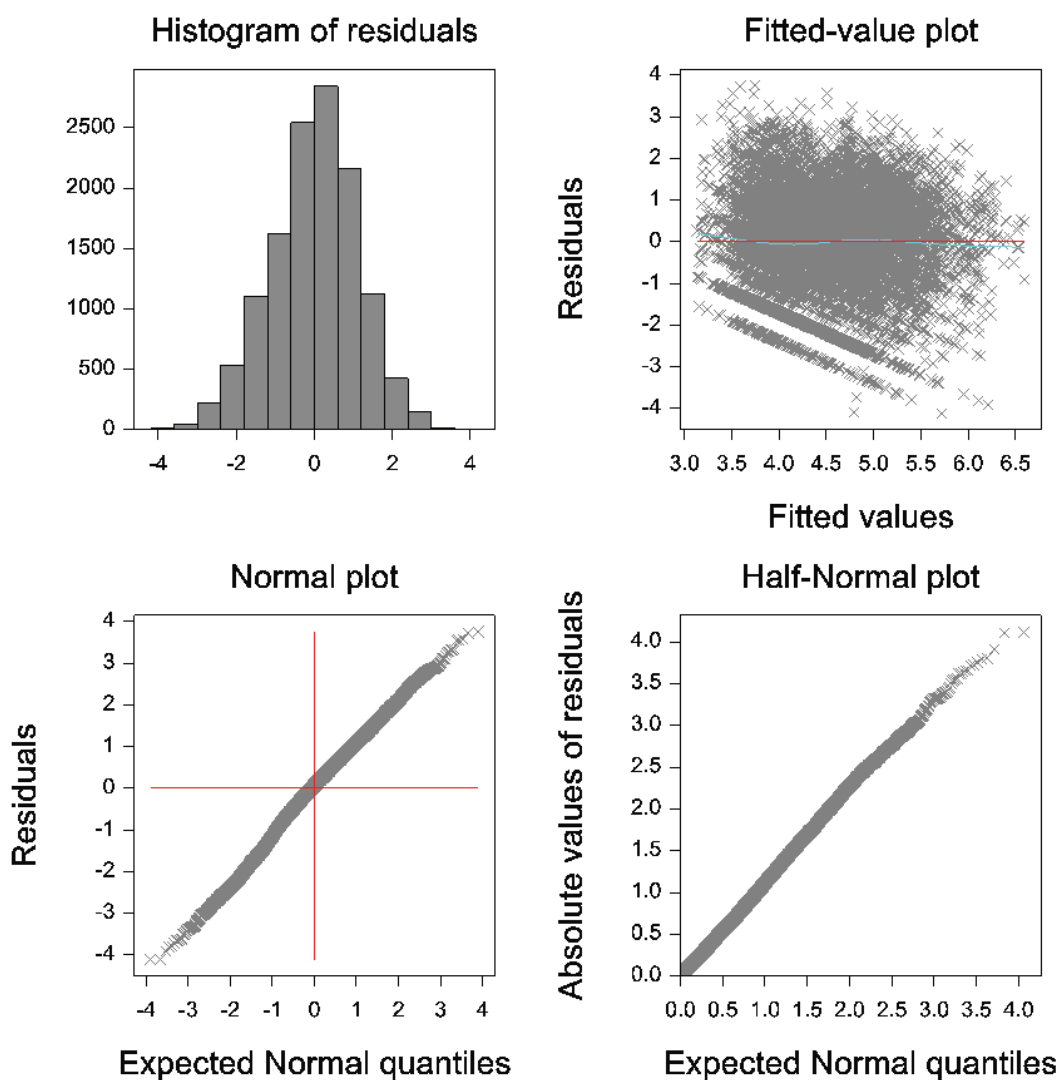
# loglery



Figure 37 Standardised residuals from the REML analysis of *L. erythropterus* shot-by-shot catches. The use of log-normal error was appropriate with no pattern in standardised residuals and linear normality plots. This result was the same for other species analysed.

Table 19 Summary of conditional analyses of trawl harvests (kg) taken per vessel trawl shot from west Gulf of Carpentaria and Arafura Sea waters, Northern Territory. Summary includes $F$ and Wald* statistics, and probabilities of no significance for fixed model terms; standard errors are shown within parentheses; – cell indicates non significant model term ($p > 0.05$); [*] binomial GLM fit.

| Conditional models | *L. erythropterus* | *L. malabaricus** | *L. sebae* | *L. johnii* | *L. argentimaculatus* | *P. multidens* |
|---|---|---|---|---|---|---|
| **Binomial GLMM** | | | | | | |
| Summary of analysis | | | | | | |
| % zero catches | 12 | 1.4 | 28.1 | 85.5 | 78.6 | 18.3 |
| Deviance: -2*LL | 54788.25 | 1697.5262 | 41926.94 | 47843.04 | 44846.41 | 57293.23 |
| Residual d.f. | 14530 | 14537 | 14530 | 14606 | 14606 | 14530 |
| Dispersion | 0.952 (0.0112) | Fixed at 1 | 1.009 (0.012) | 1.004 (0.012) | 1.014 (0.012) | 0.956 (0.0112) |
| Fixed terms | | | | | | |
| Year * zone2 | 2.72, <0.001 | 24.3*, 0.042 | 8.4, <0.001 | 5.57, <0.001 | 7.02, <0.001 | 8.05, <0.001 |
| Problem trawls | 59.89, <0.001 | – | 15.25, <0.001 | – | – | 37.13, <0.001 |
| Log trawl area | 11.25, <0.001 | 182.3*, <0.001 | 85.17, <0.001 | – | – | 118.92, <0.001 |
| Log Spanish mackerel | 29.32, <0.001 | – | 24.12, <0.001 | 26.89, <0.001 | 43.29, <0.001 | – |
| Log shark | 9.17, 0.002 | – | 47.93, <0.001 | 17.51, <0.001 | 31.33, <0.001 | 4.8, 0.028 |
| Log other fish | 139.54, <0.001 | – | 657.85, <0.001 | 227.06, <0.001 | 392.53, <0.001 | 326.61, <0.001 |
| Random terms - Variance components | | | | | | |
| Vessel | – | – | – | – | – | 0.0869 (0.1943) |
| Month | 0.0433 (0.0228) | – | 0.055 (0.026) | – | – | 0.0661 (0.0324) |
| Area | 0.7619 (0.2624) | – | 0.245 (0.094) | 0.234 (0.098) | 0.065 (0.033) | 0.5802 (0.2011) |

| Conditional models | *L. erythropterus* | *L. malabaricus* | *L. sebae* | *L. johnii* | *L. argentimaculatus* | *P. multidens* |
|---|---|---|---|---|---|---|
| **Linear mixed model** (REML) | | | | | | |
| Summary of analysis | | | | | | |
| Deviance: -2*LL | 15963.61 | 6952.48 | 510.73 | 2302.64 | 3509.49 | 2164.15 |
| Residual d.f. | 12777 | 14328 | 10450 | 2079 | 3095 | 11871 |
| Residual variance | 1.256 (0.036) | 0.583 (0.0947) | 0.341 (0.0612) | 1.017 (0.093) | 1.075 (0.057) | 0.432 (0.0398) |
| Fixed terms | | | | | | |
| Year*zone2 | 4.53, <0.001 | 18.7, <0.001 | 12.25, <0.001 | 2.39, 0.003 | 2.88, <0.001 | 11.27, <0.001 |
| Problem trawls | – | 15.45, <0.001 | – | – | – | – |
| Log trawl area | 5.81, 0.016 | 356.4, <0.001 | 5.1, 0.024 | 19.22, <0.001 | 7.06, 0.008 | 38.35, <0.001 |
| Log Spanish mackerel | – | 0.01, 0.929 | – | 6.5, 0.011 | – | – |
| Log shark | – | 3.08, 0.079 | – | 5.11, 0.024 | – | – |
| Log other fish | 241.65, <0.001 | 316.14, <0.001 | 257.82, <0.001 | 15.72, <0.001 | 37.21, <0.001 | 596.4, <0.001 |
| Random terms - Variance components | | | | | | |
| Vessel | – | 0.0092 (0.0146) | – | – | – | – |
| Month | 0.021 (0.01) | 0.0057 (0.0027) | – | – | – | – |
| Area | 0.099 (0.036) | 0.3186 (0.0947) | 0.2098 (0.0612) | 0.225 (0.093) | 0.149 (0.057) | 0.1232 (0.0398) |

## 15.4 Trap and line fish catches from Arafura Sea waters, NT.

Table 20 Example GenStat code used to analyse Arafura trap and line snapper catches.

```
"***** Conditional Binomial/log-Normal Model *****"
"Lutjanus malabaricus etc; 58.2% zeros, varies by year but skewed residuals "

calculate logeff=log(days*gearunits)
calculate logdays=log(days)
calculate logshark=log(shark+1)
calculate logcod=log(cod_ct+1)
calculate logother=log(other+mack+queenfish+salmon+1)

"General Model.binomial"
MODEL [DISTRIBUTION=binomial; LINK=logit; DISPERSION=1] problmal; nbinomial=1
FITINDIV [PRINT=model,summ,accum,estimates;CONSTANT=est;FPROB=yes;TPROB=yes;FACT=3;\
 selection=%variance,%ss,adjustedr2,r2,seobservations,dispersion,%meandeviance,%deviance,aic,sic;] \
year*method+method.logeff+method.logcod+method.loglethrinidae+method.logother;
RWALD

RCHECK [ENVELOPE=rough] resi; XMETHOD=halfnormal

TABULATE [PRINT=means; CLASSIFICATION=year,method; MARGINS=no] problmal; means=nompall
vtable table=nompall; variate=nomyearp

predict [print=desc,pred,se;predictions=binyear;se=binyearse2] year,method
vtable table=binyear; variate=binyear2
vtable table=binyearse2; variate=binyearse
print binyear2,binyearse,nomyearp

RESTRICT lmal; lmal.NE.0

VCOMPONENTS [FIXED=year*method+method.logdays+method.logother;\
 FACTORIAL=2] RANDOM=boat+area;  INITIAL=1;CONSTRAINTS=none
REML [PRINT=monitoring,model,components,effects,vcovariance,deviance,waldTests,\
covariancemodel,means; PSE=allestimates; MVINCLUDE=*; method=ai;] loglmal

vplot pen=30

vkeep [SIGMA2=ems]
vpredict [print=pred,se; PRED=LnormYear; SE=LnormYearSE] year,method
vtable table=LnormYear; variate=lnormyear
vtable table=LnormYearSE; variate=lnormyearse

print lnormyear,binyear2
calculate lmalcpue2=lmal/days
TABULATE [PRINT=means; CLASSIFICATION=year,method; MARGINS=no] lmalcpue2; means=nommeannz
vtable table=nommeannz; variate=nomyearnz

RESTRICT lmal "(unrestrict)"

" Method 2 for E(catch) with lognormal confidence intervals; backtransform + bias correct predictions to kg "
calculate BCBTLnormYear=exp(lnormyear+ems/2) "bias corrected back transformed non-zero log analysis; simple bias corrected mean, by adding half variance"
calculate BinLnormYear=binyear2*BCBTLnormYear "E(catch) = P(catch) * E(catch | catch>0)"
calculate logp=log(binyear2)
calculate varlogp=(binyearse/binyear2)**2
calculate cilog=sqrt(varlogp+lnormyearse**2)*1.96
calculate pred = exp(logp + lnormyear + ems/2) "E(catch) as above"
calculate pred_lowci = exp(logp + lnormyear + ems/2 - cilog) "lower 95% CI"
calculate pred_upci = exp(logp + lnormyear + ems/2 + cilog) "upper 95% CI"
calculate pred_lowci_nz = exp(lnormyear + ems/2 - lnormyearse*1.96) "lower 95% CI"
calculate pred_upci_nz = exp(lnormyear + ems/2 + lnormyearse*1.96) "upper 95% CI"
calculate pred_nz=BCBTLnormYear

calculate lmalcpue=lmal/days
TABULATE [PRINT=means; CLASSIFICATION=year,method; MARGINS=no] lmalcpue; means=nommeanall
vtable table=nommeanall; variate=nomyear

calculate logit2=log(binyear2/(1-binyear2))
"print results for plotting in MATLAB"
print binyear2,binyearse,logit2,pred_nz,pred_lowci_nz,pred_upci_nz,pred,pred_lowci,pred_upci,nomyear,nomyearp,nomyearnz; decimals=6
```
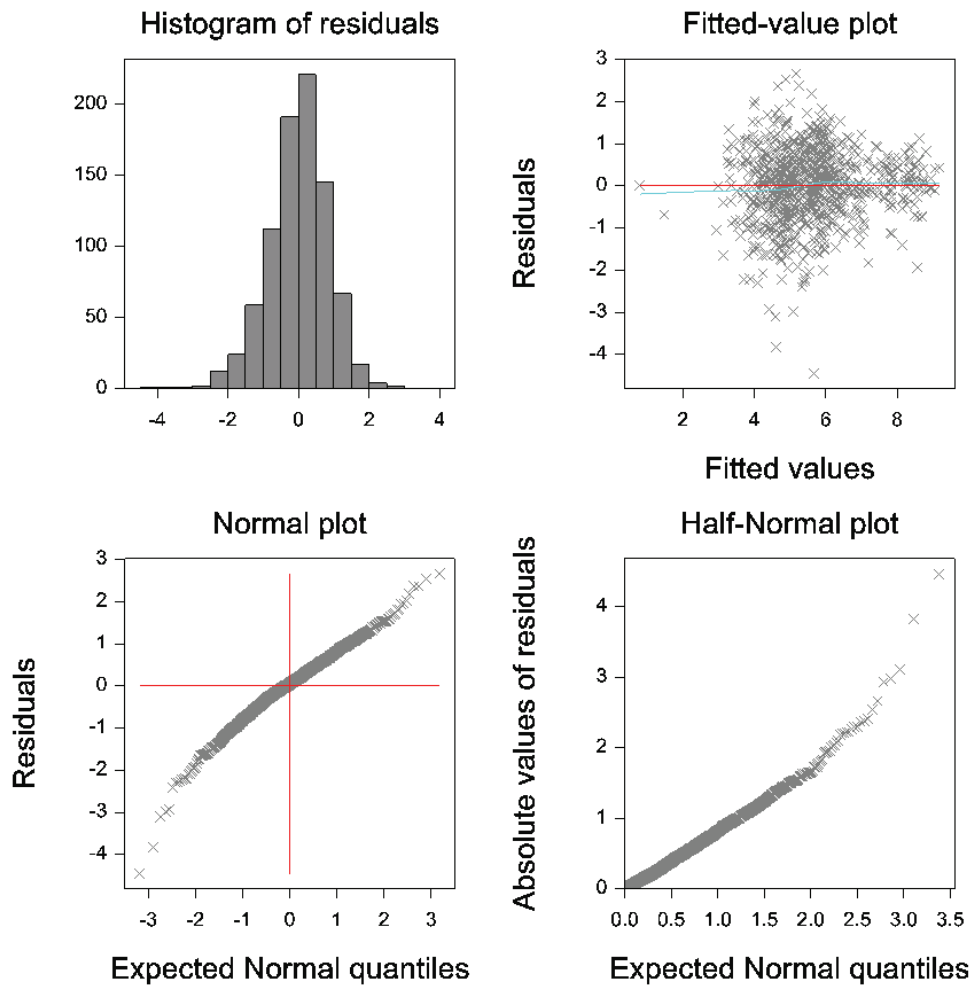
Figure 38 Standardised residuals from the REML analysis of *L. malabaricus* monthly catches by vessel and grid area. The use of log-normal error was appropriate with no pattern in standardised residuals and linear normality plots. This result was the same for other species analysed.

Table 21 Summary of conditional analyses of trap and line harvests (kg) taken per vessel month from Arafura Sea waters, Northern Territory. Summary includes *F* and Wald* statistics, and probabilities of no significance for fixed model terms; standard errors are shown within parentheses; "–" indicates non significant model term ($p > 0.05$). The more significant effort measure between logeff = log(days $*$ gearunits) or log(days) was fitted, na indicates not applied.

| Conditional models | *L. erythropterus* | *L. malabaricus* | *L. sebae* | *P. multidens* |
|---|---|---|---|---|
| **Binomial GLM** | | | | |
| Summary of analysis | | | | |
| % zero catches | 77.5 | 58.2 | 48.8 | 59.8 |
| Deviance: -2*LL | 1303.968 | 2040.664 | 1629.8231 | 1141.2511 |
| Residual d.f. | 1996 | 1996 | 2004 | 1994 |
| Dispersion | 1 | 1 | 1 | 1 |
| Fixed terms* | | | | |
| Year * method | 29.12, 0.111 | 23.16, 0.335 | 17.1, 0.706 | 14.04, 0.868 |
| Logeff.method | 21.95, <0.001 | 22.22, <0.001 | – | 166.39, <0.001 |
| Logdays.method | – | – | 58, <0.001 | – |
| Logcod.method | 88.9, <0.001 | 20.66, <0.001 | 259.4, <0.001 | 172.8, <0.001 |
| Loglethrinidae.method | 12.1, 0.002 | 12.09, 0.002 | – | 42.96, <0.001 |
| Logshark.method | 6.61, 0.037 | – | – | 4.98, 0.083 |
| Logother.method | – | 73.53, <0.001 | – | 72.23, <0.001 |

| Conditional models | *L. erythropterus* | *L. malabaricus* | *L. sebae* | *P. multidens* |
|---|---|---|---|---|
| **Linear mixed model** (REML) | | | | |
| Summary of analysis | | | | |
| Deviance: -2*LL | 759.64 | 962.48 | 1136.88 | 399.05 |
| Residual d.f. | 413 | 808 | 998 | 777 |
| Residual variance | 1.505 (0.108) | 0.865 (0.0688) | 0.872 (0.0551) | 0.360 (0.020) |
| Fixed terms | | | | |
| Year * method | 2.6, <0.001 | 4.8, <0.001 | 2.69, <0.001 | 8.77, <0.001 |
| Logeff.method | na | na | na | |
| Logdays.method | 15.04, <0.001 | 125.18, <0.001 | 106.31, <0.001 | 184.69, <0.001 |
| Logcod.method | 4.19, 0.016 | – | 42.46, <0.001 | 41.69, <0.001 |
| Loglethrinidae.method | – | – | – | 7.99, <0.001 |
| Logshark.method | – | – | – | – |
| Logother.method | – | 6.17, 0.002 | – | – |
| Random terms - Variance components | | | | |
| Vessel | 0.732 (0.269) | 0.9554 (0.2864) | 0.4291 (0.1247) | 0.7907 (0.2155) |
| Month | 0.04 (0.038) | – | – | 0.0206 (0.0115) |
| Area | 0.178 (0.108) | 0.1905 (0.0688) | 0.1844 (0.0551) | 1.2201 (0.2649) |

## 15.5 Trap and line fish catches from Timor Reef waters, NT.

Table 22 Example GenStat code used to analyse Timor trap and line snapper catches.

```
"***** Single Model *****"
"P multidens etc; 0% zeros,  but skewed residuals "

calculate logpmulti=log(pmulti) "log goldband"

MODEL [DISTRIBUTION=poisson; LINK=logarithm; DISPERSION=*] pmulti
FITINDIVIDUALLY [PRINT=model,summary,estimates,accumulated,confidence; PROBABILITY=0.95;\
 CONSTANT=estimate; FPROB=yes; TPROB=yes; FACT=2;\
selection=%variance,%ss,adjustedr2,r2,seobservations,dispersion,%meandeviance,%deviance,aic,sic;]\
 year*method+method.logdays+month+boat
RWALD
rcheck
rgraph
predict [print=desc,pred,se] year,method

"raw cpue"
calculate pmulcpue=pmulti/days
TABULATE [PRINT=means; CLASSIFICATION=year,method; MARGINS=no] pmulcpue; means=pmulcpuet
vtable table=pmulcpuet; variate=nomyearpmul
print nomyearpmul
```
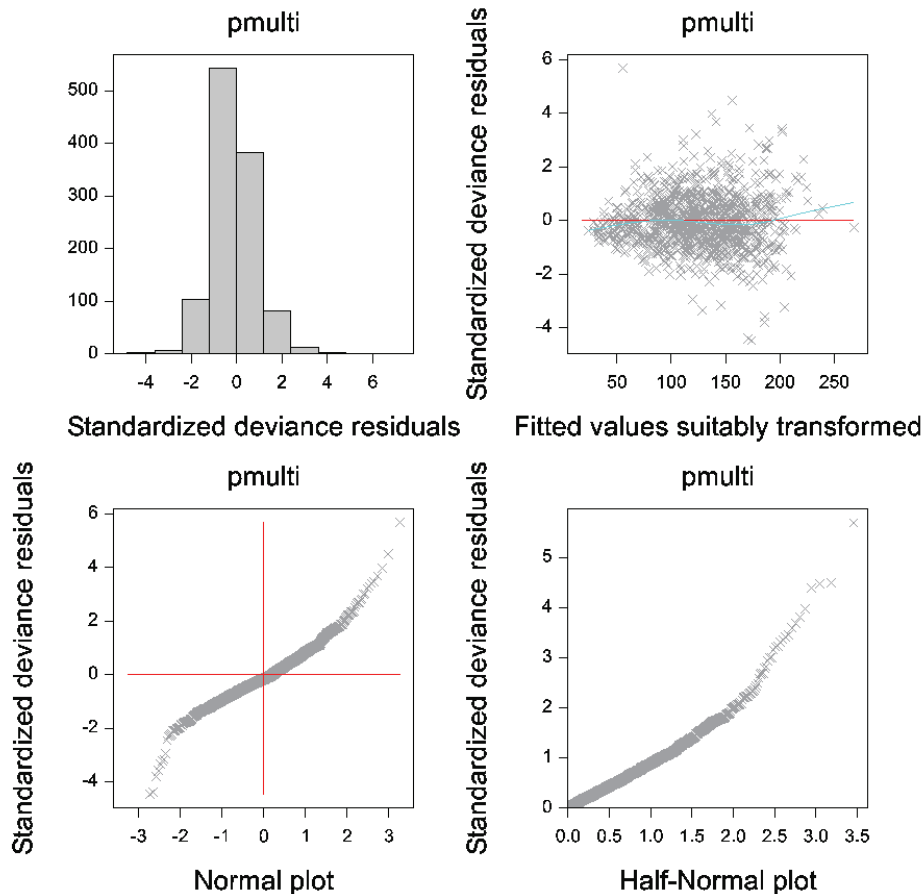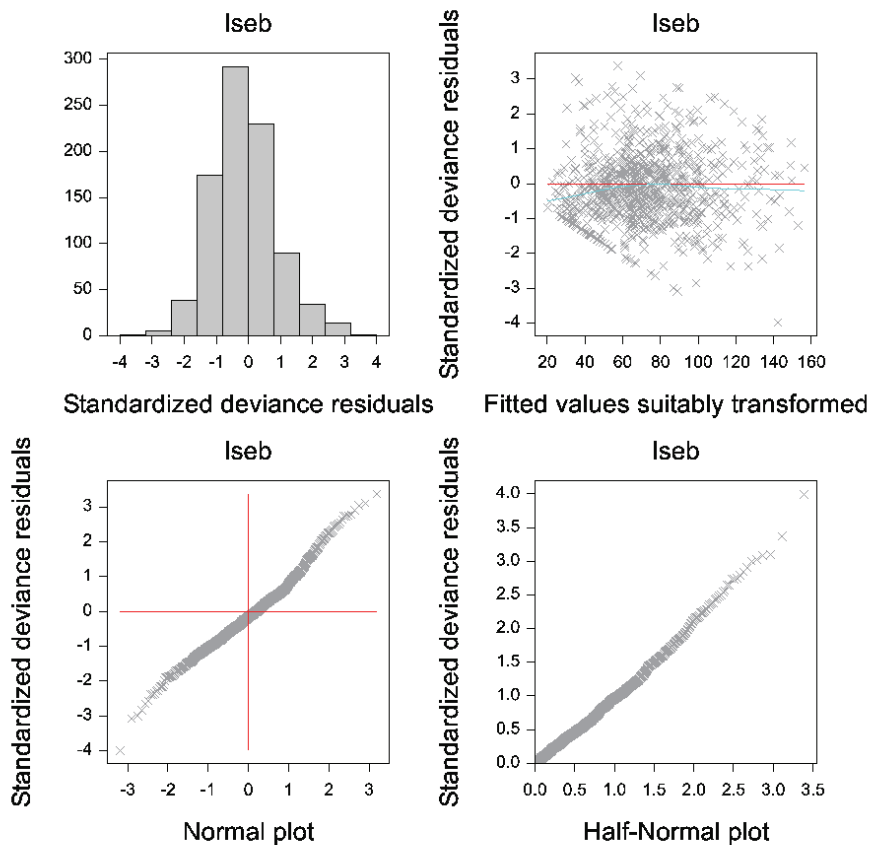


Figure 39 Standardised residuals from the GLM analysis of *P. multidens* monthly catches by vessel and grid area. The use of Poisson error and log link was appropriate with no pattern in standardised residuals and linear normality plots. This result was the same for other species analysed.

Table 23 Summary of conditional and Poisson analyses of trap and line harvests (kg) taken per vessel month from Timor Reef waters, Northern Territory. Summary includes *F* and Wald* statistics, and probabilities of no significance for fixed model terms; standard errors are shown within parentheses; – cell indicates non significant model term ($p > 0.05$); na indicates not applicable.

| Conditional models | *L. erythropterus* | *L. malabaricus* | *L. sebae* | *P. multidens* |
|---|---|---|---|---|
| **Binomial GLM** | | | | na |
| | | | | |
| Summary of analysis | | | | |
| % zero catches | 27.5 | 4.8 | 3.8 | 0 |
| Deviance: -2*LL | 823.278 | 250.0531 | 260.5752 | |
| Residual d.f. | 1074 | 1108 | 1108 | |
| Dispersion | 1 | 1 | 1 | |
| | | | | |
| Fixed terms* | | | | |
| Year * method | 49.63, <0.001 | 0.12, 1 | 0.72, 1 | |
| Logdays.method | 51.11, <0.001 | 23.79, <0.001 | 42.81, <0.001 | |
| Vessel | 92.31, <0.001 | – | – | |

| Conditional models | *L. erythropterus* | *L. malabaricus* | *L. sebae* | *P. multidens* |
|---|---|---|---|---|
| **Linear mixed model** | Yes | Yes | Yes | No |
| **Poisson GLM** | No | No | No | Yes |
| | | | | |
| Summary of analysis | | | | |
| Deviance: -2*LL | 1270.11 | 617.98 | 635.19 | 716782.9 |
| Residual d.f. | 792 | 1050 | 1062 | 1063 |
| Residual variance | 1.421 (0.229) | 0.537 (0.0637) | 0.546 (0.0287) | na |
| Dispersion | na | na | na | 674.3 |
| | | | | |
| Fixed terms | | | | |
| Year * method | 2.72, 0.003 | 5.17, <0.001 | 11.72, <0.001 | 7.57, <0.001 |
| Logdays.method | 60.48, <0.001 | 283.99, <0.001 | 281.75, <0.001 | 408.73, <0.001 |
| Vessel | na | na | na | 12.61, <0.001 |
| Month | na | na | na | 11.03, <0.001 |
| Area | na | na | na | – |
| | | | | |
| Random terms - Variance components | | | | |
| Vessel | 0.867 (0.3) | 0.5455 (0.1661) | 0.8094 (0.2239) | na |
| Month | 0.251 (0.117) | 0.0313 (0.0161) | 0.005 (0.0049) | na |
| Area | 0.353 (0.229) | 0.1108 (0.0637) | 0.0411 (0.0287) | na |

## 15.6 Trap fish catches from Kimberley waters, WA

Table 24 Example GenStat code used to analyse Kimberley trap snapper catches.

```
"Log normal"
"***** Conditional Binomial/log-Normal Model *****"

"Lutjanus sebae etc; 8.9% zeros, varies by year but skewed residuals "

"Changes spp and otherslog calculation"

"General Model."

MODEL [DISTRIBUTION=poisson; LINK=logarithm; DISPERSION=*] lseb
FITINDIVIDUALLY [PRINT=model,summary,estimates,accumulated,confidence; PROBABILITY=0.95;\
 CONSTANT=estimate; FPROB=yes; TPROB=yes; FACT=2;\
selection=%variance,%ss,adjustedr2,r2,seobservations,dispersion,%meandeviance,%deviance,aic,sic;]\
 s(lat)+s(long)+boat+logdaysfished+loghourspd+year+month
RWALD
rcheck
rgraph lat,long
predict [print=desc,pred,se] year

"raw cpue"
calculate lsebcpue=lseb/daysfished
TABULATE [PRINT=means; CLASSIFICATION=year; MARGINS=no] lsebcpue
```



Figure 40 Standardised residuals from the GLM analysis of *L. sebae* monthly catches by vessel and grid area. The use of Poisson distribution and log link was appropriate with no pattern in standardised residuals and linear normality plots. This result was the same for other species analysed.

Table 25 Summary of conditional and Poisson analyses of trap harvests (kg) taken per vessel month from Kimberley waters, Western Australia. Summary includes: *F* and chi-squared[*] statistics and probabilities of no significance for fixed model terms; standard errors are shown within parentheses; – cell indicates non significant model term ($p > 0.05$); na indicates not applicable.

| Conditional models | *L. erythropterus* | *L. malabaricus* | *L. sebae* | *L. argentimaculatus* | *P. multidens* |
|---|---|---|---|---|---|
| **Binomial GLM** | | na | na | | na |
| Summary of analysis | | | | | |
| % zero catches | 48.9 | 13.8 | 6.5 | 51.4 | 1.4 |
| Deviance: −2∗LL | 880.907 | | | 724.456 | |
| Residual d.f. | 840 | | | 840 | |
| Dispersion | 1 | | | 1 | |
| Fixed terms* | | | | | |
| Year | 62.62, <0.001 | | | 86.32, <0.001 | |
| Logdays | 9.19, 0.002 | | | 6.22, 0.013 | |
| Vessel | 52.2, <0.001 | | | 106.43, <0.001 | |
| Month | 20.33, 0.041 | | | 21.86, 0.025 | |
| Spline (latitude) | 4.589, 0.001 | | | 12.5485, <.001 | |
| Spline (longitude) | – | | | – | |

| Conditional models | *L. erythropterus* | *L. malabaricus* | *L. sebae* | *L. argentimaculatus* | *P. multidens* |
|---|---|---|---|---|---|
| **Linear mixed model** | Yes | No | No | Yes | No |
| **Poisson GLM** | No | Yes | Yes | No | Yes |
| Summary of analysis | | | | | |
| Deviance: -2*LL | 679.80 | 249105.6 | 369851.7 | 377.94 | 889168.6 |
| Residual d.f. | 434 | 840 | 836 | 413 | 991 |
| Residual variance | 1.463 (0.102) | na | na | 0.763 (0.054) | na |
| Dispersion | Na | 296.6 | 442.4 | na | 897.2 |
| Fixed terms | | | | | |
| Year | 3.76, <0.001 | 18.74, <0.001 | 14.62, <0.001 | 3.98, <0.001 | 14.03, <0.001 |
| Logdays | 124.54, <0.001 | 533.68, <0.001 | 634.2, <0.001 | 170.45, <0.001 | 1089.3, <0.001 |
| Vessel | Na | 12.48, <0.001 | 12.78, <0.001 | na | 10.49, <0.001 |
| Month | Na | 2.03, 0.024 | 2.98, <0.001 | na | 10.28, <0.001 |
| Spline (latitude)* | Na | – | 3.98, 0.003 | na | 22.35, <.001 |
| Spline (longitude)* | Na | 45.37, <0.001 | 4.41, 0.002 | na | 14.54, <.001 |
| Random terms - Variance components | | | | | |
| Vessel | 0.862 (0.456) | na | na | 0.5371 (0.2995) | na |
| Month | 0.009 (0.022) | na | na | – | na |
| Spline (latitude) | – | na | na | 0.4674 (0.376) | na |
| Spline (longitude) | 0.287 (0.332) | na | na | – | na |

# 16  APPENDIX 4: FISH AGE FREQUENCIES

This appendix documents historic fish age frequencies. The plots were structured by year and species to show sample numbers and missing years. The collation of data was up to 2009. The observed age frequencies are represented by bars and predicted frequencies (model fitted, run producing the highest likelihood) by red lines. Sample sizes are shown for actual numbers of fish ('n') and effective sample sizes ('ess'). The ess adjusted for data variance and correlation in sampling: it reflects the number of fish that would comprise a sample with the same age-structure precision if the fish could be sampled in an independent and identically distributed (i.i.d.) manner from the whole population.

Lack of fit to observed age frequencies results in low effective sample sizes and can be due to a combination of

- observation error, such as schooling of fish by age, which gives the appearance of non-representative sampling; and
- process error, such as annual variation in the age at recruitment to the fishery, which is not covered by the population model.

Figure 41 Age frequencies by year and species from east Gulf of Carpentaria waters, Queensland.
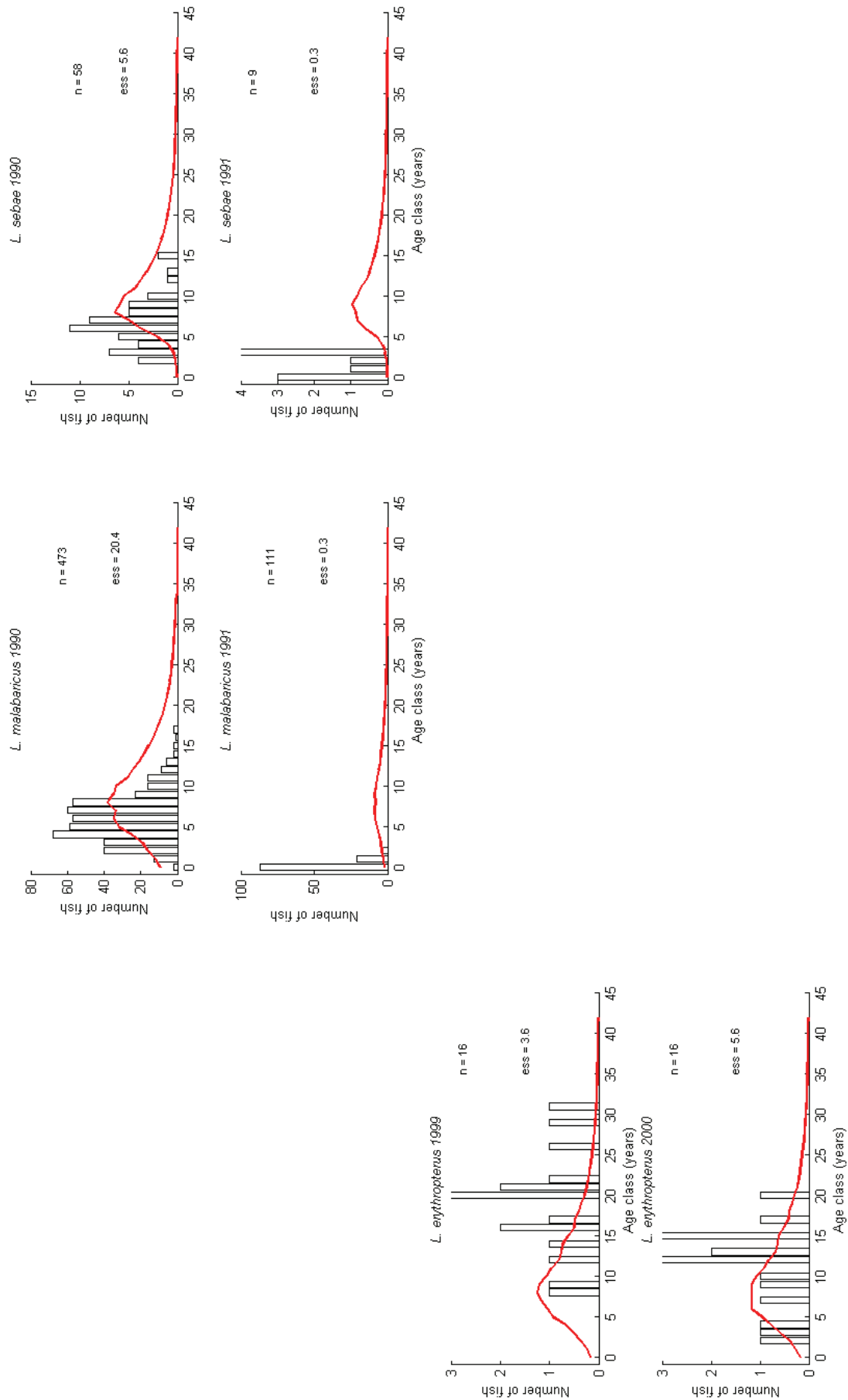
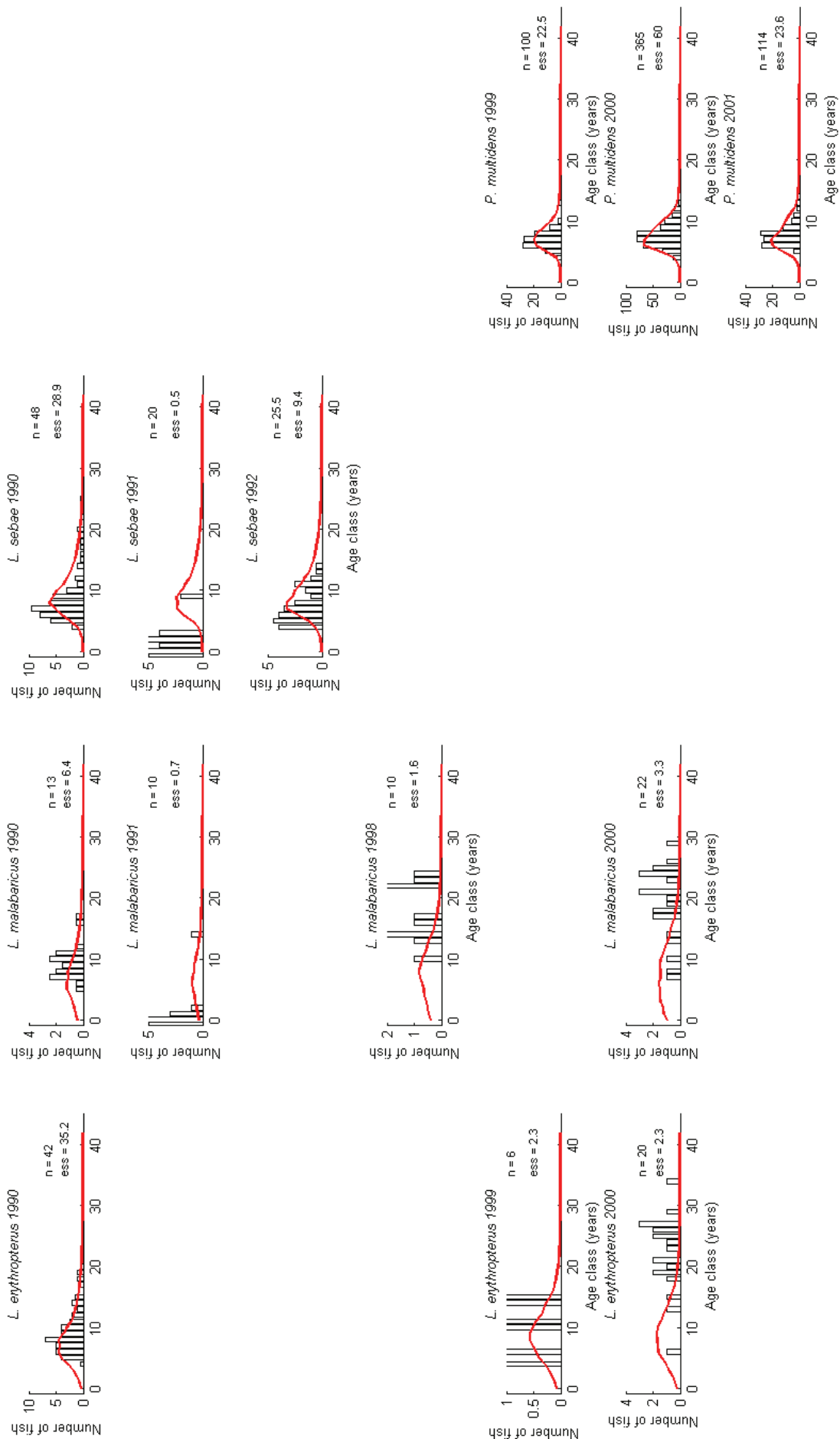Figure 42 Age frequencies by year and species from west Gulf of Carpentaria waters, Northern Territory.

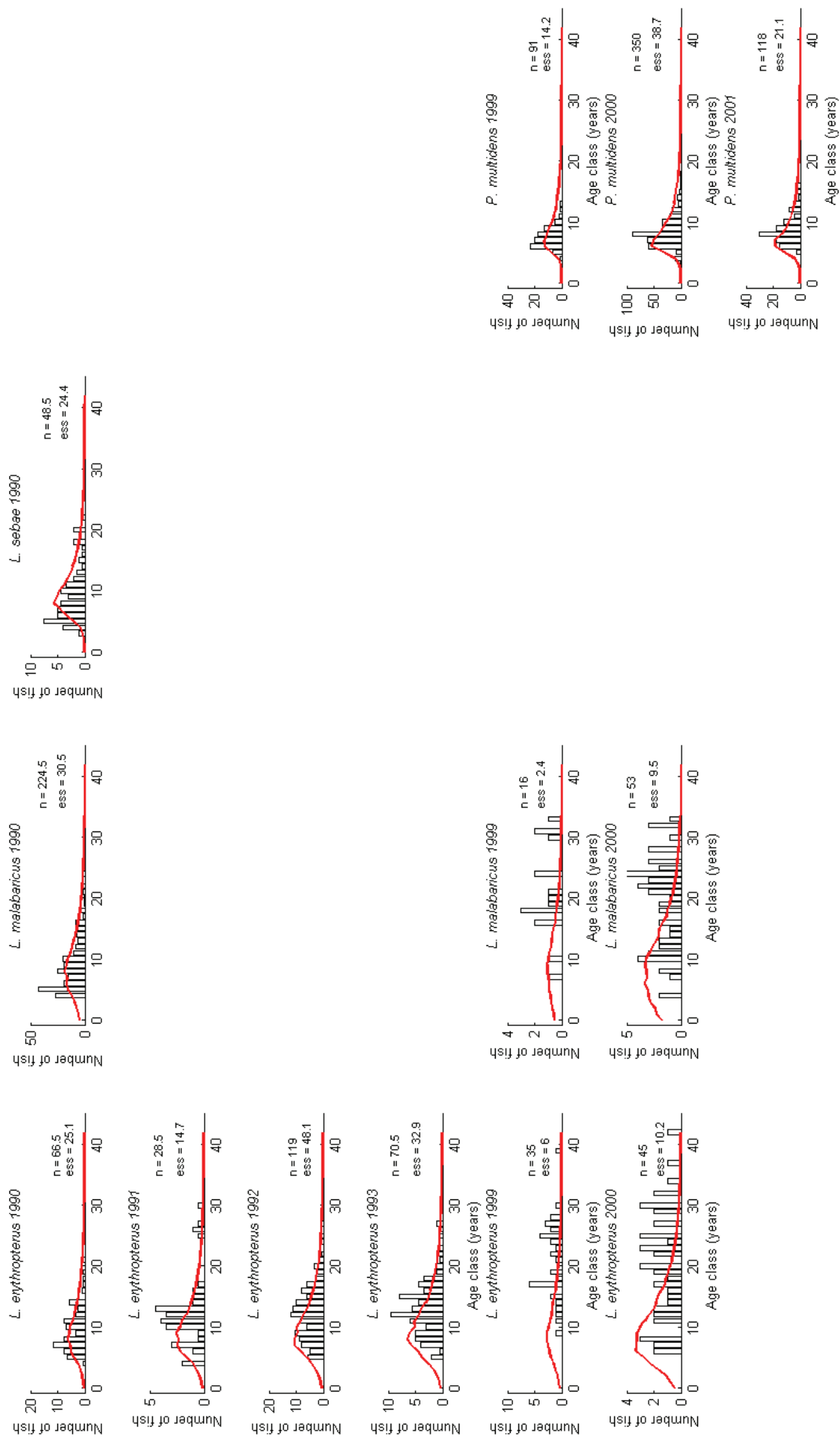Figure 43 Age frequencies by year and species from Arafura Sea waters, Northern Territory.

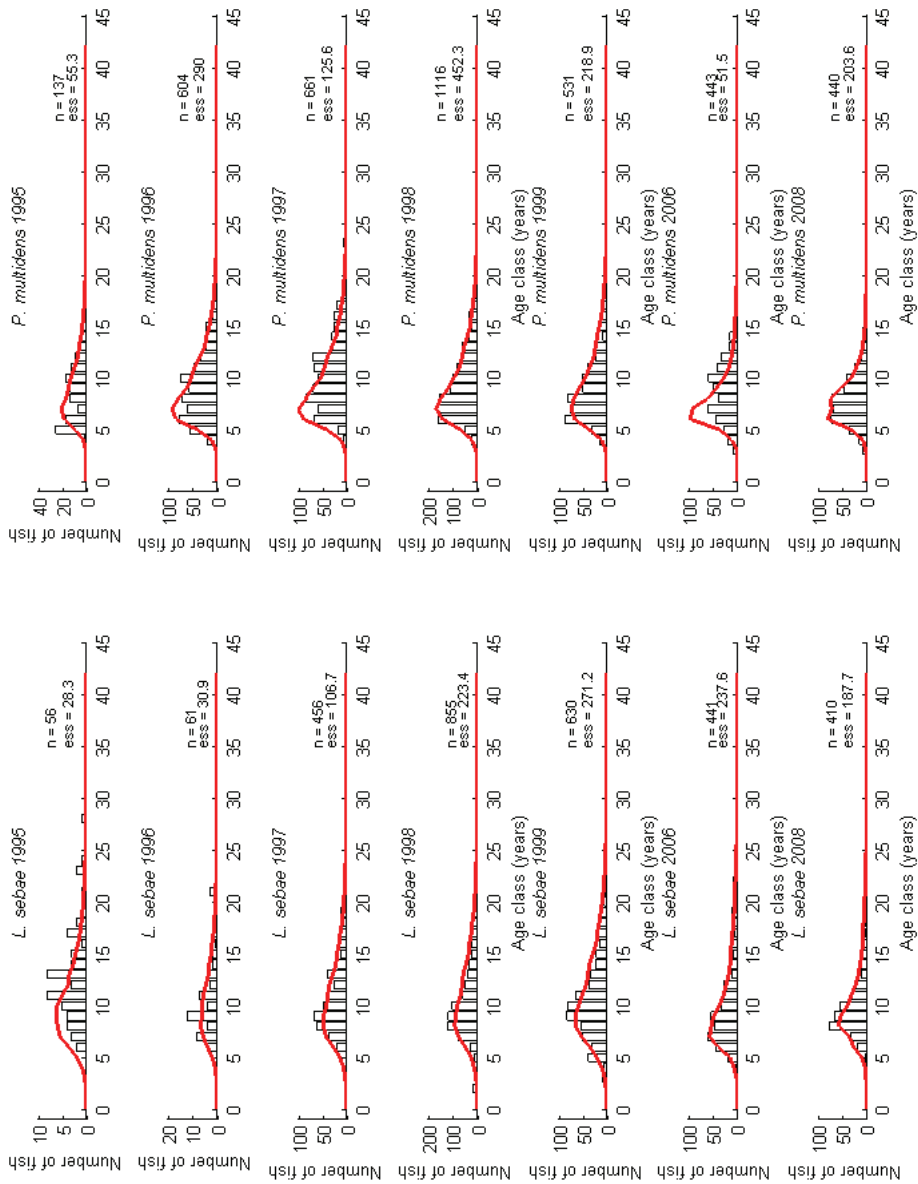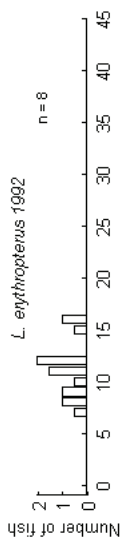Figure 44 Age frequencies by year and species from Timor Reef waters, Northern Territory.

Figure 45 Age frequencies by year and species from Kimberley waters, Western Australia.
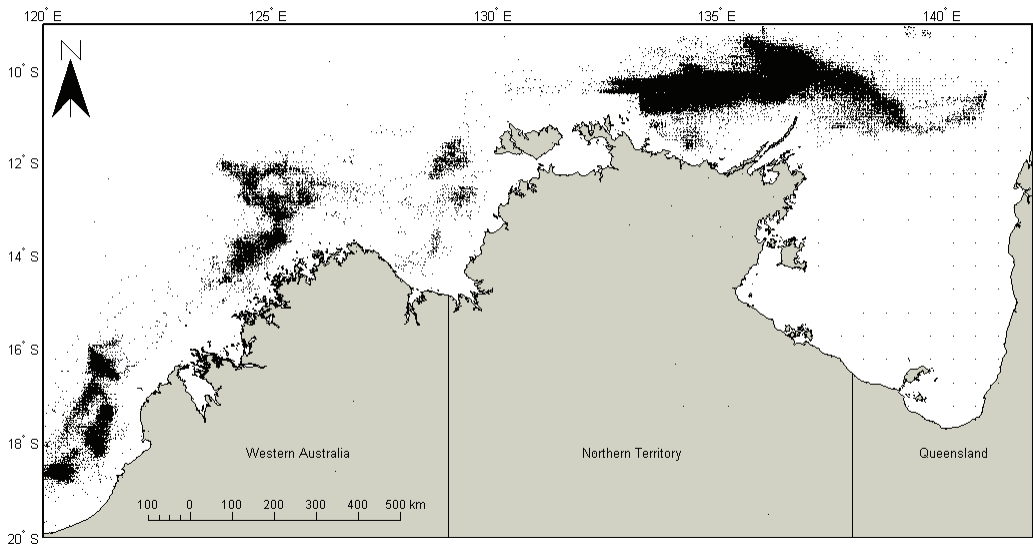
## 17 APPENDIX 5: FOREIGN FISHING LOCATION MAPS



Figure 46 Distribution of unique fish trawling locations by foreign vessels prior 1990. The northern Australian data was sourced from ABARES Metadata 37, section 19 appendices. The spread of points indicated the coarseness of latitude and longitude data.
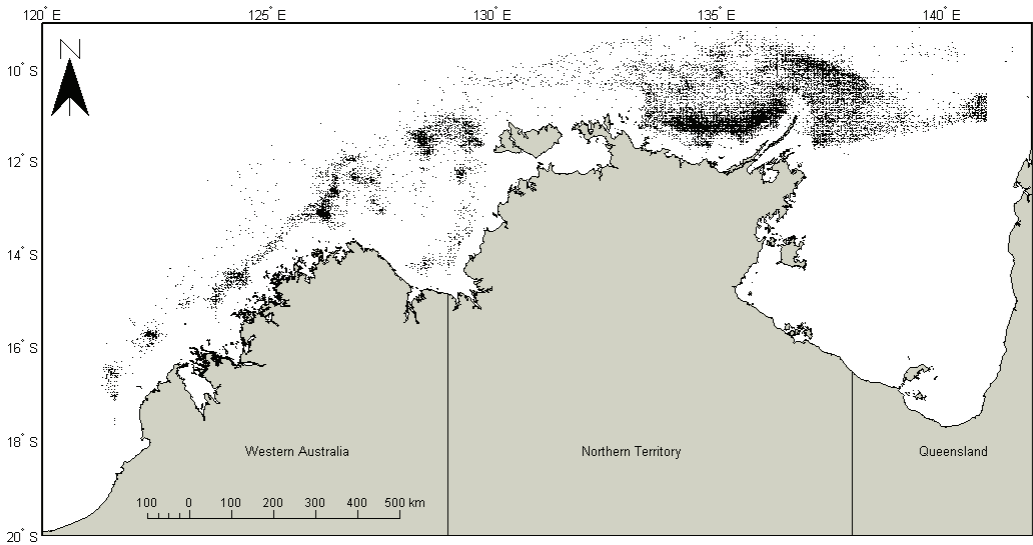


Figure 47 Distribution of unique fish gill net locations by foreign vessels prior 1990. The northern Australian data was sourced from ABARES Metadata 37, section 19 appendices. The spread of points indicated the coarseness of latitude and longitude data.

# 18 APPENDIX 6: MORE CALIBRATION AND ASSESSMENT OUTPUTS

Table 26 Species CAAB codes, pictures and approximate biological parameters. The relationship for length-weight is expressed as $w = aL^b$, von Bertalanffy growth as $L = L_\infty \left[ 1 - \exp\{-K(t - t_0)\} \right]$ and logistic female maturity as $\text{mat} = 1 / \left[ 1 + \exp\{-\log(19)(a - a_{50}) / (a_{95} - a_{50})\} \right]$. Lengths are measured in cm, weights in kg and ages in yr; the von Bertalanffy growth parameter $K$ is measured in $\text{yr}^{-1}$.

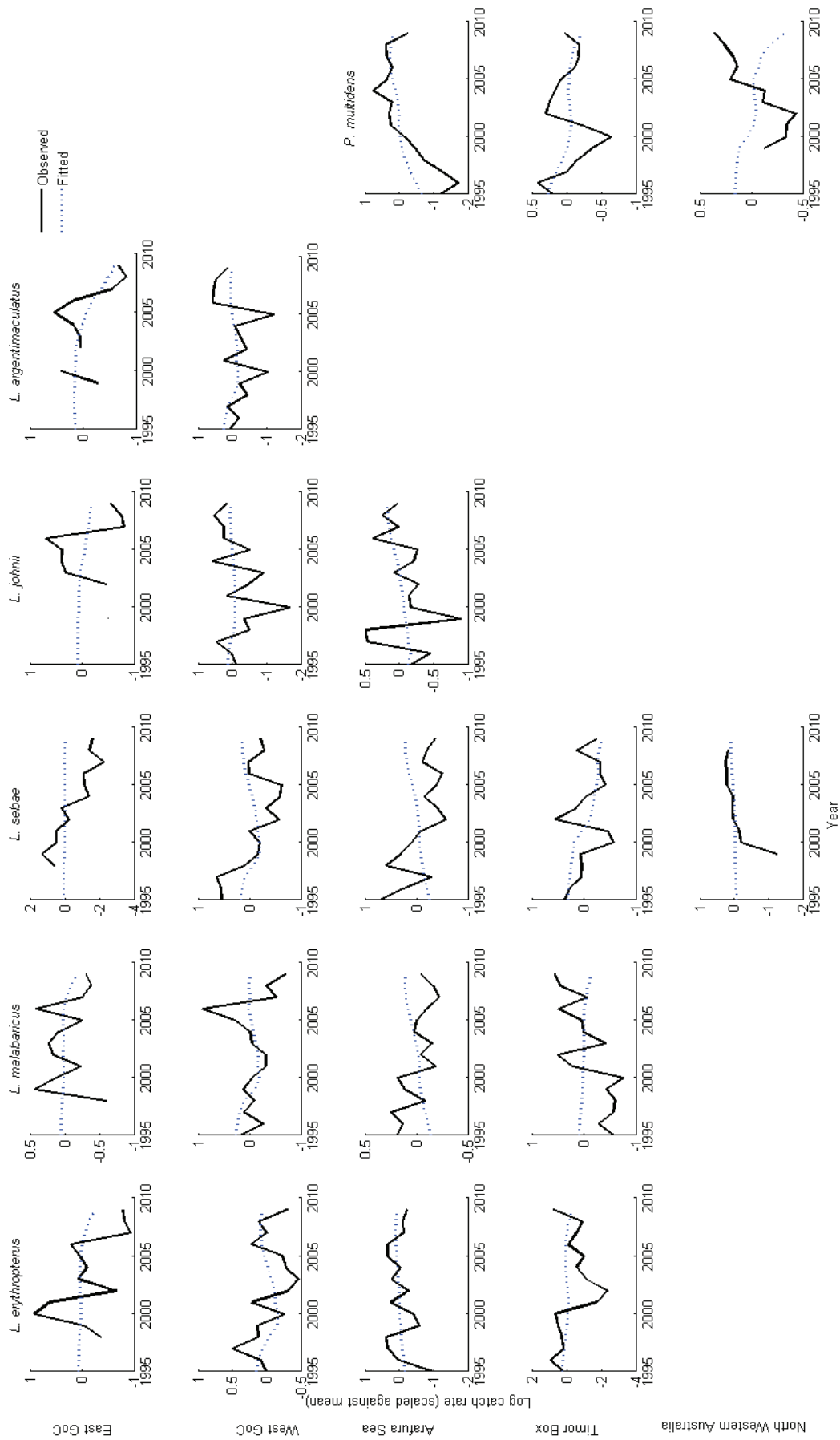| Species and CCAB code | | Length-weight (a; b) | Male and female growth $(L_\infty; K; t_0)$ | Female maturity $(a_{50}; a_{95})$ |
|---|---|---|---|---|
| Crimson snapper (*Lutjanus erythropterus*) 37 346005 Picture: CSIRO MAR |  | 0.0000244; 2.87 | 58.45; 0.3922; 0.1768 58.45; 0.3922; 0.1768 | 5; 7 |
| Saddletail snapper (*Lutjanus malabaricus*) 37 346007 Picture: CSIRO MAR |  | 0.0000234; 2.879 | 68.64; 0.180; −0.33 56.58; 0.262; −0.09 | 9; 12 |
| Red emperor (*Lutjanus sebae*) 37 346004 Picture: CSIRO MAR |  | 0.0000172; 3.057 | 62.78; 0.1511; −0.5947 48.26; 0.2710; 0.0650 | 10; 13 |
| Golden snapper (*Lutjanus johnii*) 37 346030 Picture: Queensland DEEDI |  | 0.0000144; 2.993 | 76.5; 0.152; −1.35 76.5; 0.152; −1.35 | 10; 13 |
| Mangrove Jack (*Lutjanus argentimaculatus*) 37 346015 Picture: Queensland DEEDI |  | 0.0000133; 3.045 | 67.7; 0.150; −1.313 64.2; 0.204; −0.393 | 8; 11 |
| Goldband snapper (*Pristipomoides multidens*) 37 346002 Picture: NFRDI, Korea |  | 0.0000221; 2.95 | 59.81; 0.1873; −0.173 59.81; 0.1873; −0.173 | 6; 8 |

Figure 48 Comparison of log-observed and model log-predicted catch rates by sector (row plots) and species (column plots). Predicted (dotted blue lines) values represent approximate maximum likelihood fits.

## 19 APPENDIX 7: METADATA

Table 27 List of collated tropical snapper data.

| Number | Title | Format | Size (mb) | Custodian/source | Jurisdictions | Description | Date sourced |
|---|---|---|---|---|---|---|---|
| 1 | qld_qpif_DR1702_GOC_Lutjanidae_catches.mdb | MSAccess | 33 | DEEDI, Qld | Gulf of Carpentaria | Commercial trawl and inshore catch and effort; including charter etc; plus trawl VMS data. | Sep-2009 |
| 2 | qld_qpif_redsnapper_biodata_7Oct09.mdb | MSAccess | 1.2 | DEEDI, Qld | Gulf of Carpentaria | LTMP monitoring data; FL and ages | Oct-2009 |
| 3 | qld_rec_snapper_catches.mdb | MSAccess | 7 | DEEDI, Qld | Gulf of Carpentaria | Recreational catch data | Jul-2010 |
| 4 | Crimson Snapper tagged and recaptured.xls | Excel | 1 | SunTag; Infofish | Queensland; mostly east coast | tag data | Jul-2010 |
| 5 | Golden Snapper tagged and recaptured.xls | Excel | 1 | SunTag; Infofish | Queensland; mostly east coast | tag data | Jul-2010 |
| 6 | Mangrove Jack tagged and recaptured.xls | Excel | 6 | SunTag; Infofish | Queensland; mostly east coast | tag data | Jul-2010 |
| 7 | Mangrove Jack tagged and recaptured_Recaptures.xls | Excel | 0.3 | SunTag; Infofish | Queensland; mostly east coast | tag data | Jul-2010 |
| 8 | Mangrove Jack tagged and recaptured_Releases.xls | Excel | 2 | SunTag; Infofish | Queensland; mostly east coast | tag data | Jul-2010 |
| 9 | Red Emperor tagged and recaptured.xls | Excel | 2.5 | SunTag; Infofish | Queensland; mostly east coast | tag data | Jul-2010 |
| 10 | Saddletail Snapper tagged and recaptured.xls | Excel | 1 | SunTag; Infofish | Queensland; mostly east coast | tag data | Jul-2010 |
| 11 | Map Grids 3 updated.xls | Excel | 0.7 | SunTag; Infofish | Queensland | tag location data | Jul-2010 |
| 12 | A1 & A2 gold snap & mgv jack.mdb | MSAccess | 26 | DoR-Fisheries, NT. | NT inshore | AI and A2 fisheries with golden snapper and mangrove jack commercial catch and effort. | May-2010 |
| 13 | FRDC2009-037_NT_observer&survey_data.mdb | MSAccess | 21 | DoR-Fisheries, NT. | Timor Reef, Arafura Sea | 1989-2009 | Oct-2009 |
| 14 | NT_Finfish trawl.mdb | MSAccess | 146 | DoR-Fisheries, NT. | Gulf of Carpentaria, Arafura Sea | A16 Trawl shot-by-shot catch and effort. | Feb-2010 |
| 15 | NT_Finfish_A6_demersal.mdb | MSAccess | 94 | DoR-Fisheries, NT. | Arafura Demersal | Commercial line and trap catch and effort. | Mar-2010 |
| 16 | NT_Finfish_A18_timor.mdb | MSAccess | 228 | DoR-Fisheries, NT. | Timor Reef | Commercial line and trap catch and effort. | Mar-2010 |
| 17 | nt_logbook_VariableDescription.doc | Word | 0.032 | DoR-Fisheries, NT. | NT offshore | Field definitions + plus see email pst file. | Feb-2010 |
| 18 | P.mult Arafura and Timor.xls | Excel | 2.5 | DoR-Fisheries, NT. | Timor Reef, Arafura Sea | age data | Nov-2010 |
| 19 | Red emperor_MF_ages.xls | Excel | 0.1 | DoR-Fisheries, NT. | Timor Reef, Arafura Sea | age data; link to FRDC2009-037_NT_observer&survey_data.mdb | Oct-2009 |

| 20 | Red emperor_Trawl samples.xls | Excel | 0.05 | DoR-Fisheries, NT. | Timor Reef, Arafura Sea | LF,age,Otolith wt; link to FRDC2009-037_NT_observer&survey_data.mdb | Oct-2009 |
|---|---|---|---|---|---|---|---|
| 21 | saddletail snapper_Trawl survey samples.xls | Excel | 0.8 | DoR-Fisheries, NT. | Timor Reef, Arafura Sea | LF,age,Otolith wt; link to FRDC2009-037_NT_observer&survey_data.mdb | Oct-2009 |
| 22 | VBGF_L.erythrop_constrained_090702.xls | Excel | 0.2 | DoR-Fisheries, NT. | Timor Reef, Arafura Sea | age data; link to FRDC2009-037_NT_observer&survey_data.mdb | Oct-2009 |
| 23 | Juv Snapper data from G Fry.xls | Excel | 0.3 | CSIRO and NT | NT inshore | Multiple sheets. Catch and specimen tables linked using Landing_ID. Specimen, Morphometrics and Aging tables linked using FishID. Lmal, Lery, Pmul. | Jul-2010 |
| 24 | redsnapper_csiro.mdb | MSAccess | 4 | CSIRO | Gulf of Carpentaria, Arafura Sea | Soviet foreign fishing data. Includes 3 tables for location, catch and effort, and fish length frequencies. | Dec-2009 |
| 25 | OTOLITHS PRE 1993.xls | Excel | 0.112 | CSIRO | Gulf of Carpentaria | Lmal and Lery. Pre 1993 data does not specify left or right otolith - they were called otolith 1 and ototlith 2. Otolith 1 has age data associated with it. N=1070. | Dec-2009 |
| 26 | OTOLITHS POST 1993.xls | Excel | 0.045 | CSIRO | Gulf of Carpentaria | L mal and Lery, with some measured increments. N=403. | Dec-2009 |
| 27 | SS0390_LFREQ.xls | Excel | 0.096 | CSIRO | Gulf of Carpentaria | Lmal, Lery, Lseb, Ljon, Larg. n=1889. Standard length mm. | Jan-2010 |
| 28 | SS0591_LFREQ.xls | Excel | 0.036 | CSIRO | Gulf of Carpentaria | Lmal, Lery, Lseb, Ljon, Larg. n=711. Standard length mm. | Jan-2010 |
| 29 | SS_BIOMASS_SNAPPER_CATCH.xls | Excel | 0.23 | CSIRO | Gulf of Carpentaria | Southern Surveyor snapper catch data from biomass surveys carried out during the following voyages: SS199301, SS199003, SS199105, SS199307. Operation table. Catch rate data. Lmal, Lery, Lseb, Ljon, Larg. | Jan-2010 |
| 30 | | | | CSIRO | Gulf of Carpentaria | There are three other fish biomass surveys that were carried out aboard Soela in 1980 and 1981 - I have just tracked down info about some of the issues that I have with the data (pers com. Miller, M.); S0198005, SO198007, SO198102. | No |
| 31 | wa_data_frdc2009_037.mdb | MSAccess | 2 | Fisheries, WA | Kimberley offshore fishery | Monthly trap and line catches. | Nov-2009 |
| 32 | Lsebae Kimb age data.xls | Excel | 1 | Fisheries, WA | Kimberley offshore fishery | Age data | Oct-2010 |
| 33 | multidens1995-99age structure.xls | Excel | 2 | Fisheries, WA | Kimberley offshore fishery | Age data | Oct-2010 |
| 34 | 08 multidens ages.xls | Excel | 0.05 | Fisheries, WA | Kimberley offshore fishery | Age data | Oct-2010 |
| 35 | biologicalagedumpOct2006-multidens.xls | Excel | 0.24 | Fisheries, WA | Kimberley offshore fishery | Age data | Oct-2010 |
| 36 | NDSFRedSnapperData2000-2009updated.xls | Excel | 0.8 | Fisheries, WA | Kimberley offshore fishery | Monthly trap and line catches. | Jan-2010 |
| 37 | foreign_gn_tw.mdb | MSAccess | 400 | ABARES | Australia | Foreign gill net and trawling data. Includes 7 tables for location, boat, operation and species catch. | Dec-2009 |
| 38 | P.mult age and lat longs.xls | Excel | 0.5 | DoR-Fisheries, NT. | Timor Reef, Arafura Sea | Age data with capture dates and sites, including biological and marginal increment data. | Feb-2011 |
| 39 | Tropical snapper data 1990-1998.xls | Excel | 5.8 | Fisheries, WA | Kimberley offshore fishery | Monthly trap and line catches. | May-2011 |
| 40 | P.mult age and lat longs.xls | Excel | 0.5 | DoR-Fisheries, NT. | Timor Reef, Arafura Sea | Age data with capture dates and sites, including biological and marginal increment data. | Feb-2011 |

**Queensland Government**
**Department of Employment, Economic Development and Innovation**
**Queensland Primary Industries and Industries**

**Media Release**
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**Project ensures red snapper stocks for future**

A new collaborative project between State Governments and Australian Government agencies will ensure the northern Australian red snapper industry between the Kimberley and Cape York remains sustainable and profitable for the future.

Queensland Primary Industries and Fisheries principal scientist Michael O'Neill said the aim of the red snapper project was to provide a means of assessing the health of the fishery by using new monitoring techniques and reference points.

"We're developing new methods for monitoring five species of red snapper in the Gulf of Carpentaria, waters off the Northern Territory and the northern part of Western Australia," he said.

"In addition, we will design a survey with the commercial fishing industry to collect data using trawl vessels to trawl different sites and provide an indication of what the stock levels are at each site.

"The survey will ensure the proper understanding of the status of red snapper stocks and industry will be engaged throughout the project.

"Industry will be fundamental to the endorsement of the methodology and decision rules that are developed."

About 1500-1800 tonnes of red snapper are caught across northern Australia each year, with a landings value of $6-8 million.

Mr O'Neill said in the past, limited data, the species' longevity (30–40 years) and unquantifiable external catch had compromised fishery assessments.

"Therefore, improved fishery monitoring and management in the Australian Fishing Zone is needed to ensure the sustainability and commercial profitability of red snappers," he said.

"The survey will allow the capture of meaningful data and will provide accurate information for fisheries managers to plan for the future."

The project is receiving Fisheries Research and Development Corporation funding, along with contributions from the Queensland, Northern Territory and Western Australian governments; the Bureau of Rural Sciences and CSIRO.

**Caption:** The project to ensure the sustainability and profitability of the northern Australian red snapper industry is due for completion in October 2010.

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