Stock assessment of Golden Snapper (Lutjanus johnii) in the Northern Territory 2021

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Document title	Stock assessment of Golden Snapper (Lutjanus johnii) in the Northern Territory 2021
Contact details	NT Fisheries
Approved by	
Date approved	
Document review	
TRM number	

Version	Date	Author	Changes made
1.01	13 September 2023	Deepak Pazhayamadom	Stock Synthesis model
1.02	2 October 2023	Jo Randall	Expanded and formatted
1.03	23 January 2024	Michael Usher	Stock Reduction Analysis
1.04	16 February 2024	Deepak Pazhayamadom	Catch-MSY
1.05	19 March 2024	Jo Randall	Introduction & draft review
1.06	22 March 2024	Deepak Pazhayamadom	Biomass & harvest fractions
1.08	8 August 2024	Sandra Curin-Osorio	Model diagnostics
1.09	12 August 2024	Deepak Pazhayamadom	Reviewed & formatted
1.10	24 September 2024	Deepak Pazhayamadom	Revised Stock Synthesis model
1.11	8 October 2024	Michael Usher	Final review

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1. Summary

This document provides quantitative assessments of Golden Snapper that estimate the status of three assessment units in the Northern Territory for 2021. The 'Greater Darwin Region' assessment unit is assessed using a Stock Synthesis model, while the 'Regional Northern Territory' and the 'Gulf of Carpentaria' assessment units are assessed using the outcomes of Catch-Maximum Sustainable Yield models and independent fishing survey data.

The model for the Greater Darwin Region estimated that biomass has declined significantly from 1970 to 2015. A decline in fishing mortality since 2010 has resulted in an increasing trend in biomass. However, the median biomass in 2021 is estimated at 21% of the unfished level, with the confidence interval ranging from 13% to 29%. The median fishing mortality relative to MSY in 2021 is estimated at 2.1, with the confidence interval ranging from 1.35 to 2.82. This level of fishing mortality (i.e. >1) is expected to prevent any further recovery.

On the basis of the evidence provided above, Golden Snapper in the **Greater Darwin Region** is classified as **Depleting**.

The Regional Northern Territory assessment unit is data limited and has been assessed using multiple lines of evidence. Outcomes of Catch-MSY modelling and harvest fractions derived from a fishery independent survey provide evidence for the sustainability of Golden Snapper in this assessment unit. The Catch-MSY model determined that the median biomass remained stable between 78% to 85% of unfished level for the last 20 years with no significant change in fishing pressure during this period. The model shows that the median biomass in 2021 is estimated at 84% of unfished level, with the confidence interval ranging from 39% and 95%. A fishery independent survey indicates that the harvest fraction of Golden Snapper in 2021 is 1.9% of the estimated biomass with a confidence interval from 1.1% to 6.9%.

On the basis of the evidence provided above, Golden Snapper in **Regional Northern Territory** are classified as **Sustainable**.

The Gulf of Carpentaria assessment unit is data limited and has been assessed using multiple lines of evidence. Outcomes of Catch-MSY modelling and harvest fractions derived from a fishery independent survey provide evidence for the sustainability of Golden Snapper in this assessment unit. The Catch-MSY model determined that the median biomass remained stable at around 75% of unfished levels until 1992 and have increased since late 1990's as a result of a reduction in catch. The model shows that the median biomass in 2021 is estimated at 90% of unfished level, with the confidence interval ranging from 60% to 97%. A fishery independent survey indicates that the harvest fraction of Golden Snapper in 2021 is 0.59% of the estimated biomass with a confidence interval from 0.34% to 2.1% of the estimated biomass.

On the basis of the evidence provided above, Golden Snapper in the **Gulf of Carpentaria** are classified as **Sustainable**.

2. Introduction

2.1. Species biology

Golden Snapper is one of 65 species of the genus *Lutjanus* from the Lutjanidae family. It is widely distributed throughout the Indo-West Pacific, inhabiting tropical inshore waters from East Africa to Fiji and northern Australia to Taiwan (Allen, 1985). The distribution of this species within Australian waters extends from the Kimberley region in Western Australia, around the north of the continent to the southern Great Barrier Reef (around Rockhampton) (Travers et al., 2010).

The current life history paradigm for Golden Snapper is complex with distinct inshore and offshore phases. In estuaries and near-shore embayment, Golden Snappers are predominantly juveniles and sub-adults, while most fish encountered on coastal near-shore and offshore reefs are larger adult fish (Hay, 2006; Kiso and Mahyam, 2003). The larger fish prefer to inhabit reefs, rocks and pinnacles in both deep and shallow habitats within these areas (Hay, 2006; Travers et al., 2010) and move about on the nearby sandy areas possibly to feed (Cappo et al., 2013; Kiso and Mahyam, 2003). Golden Snapper are gonochoristic (i.e. separate sexes throughout life) and can grow to at least 90cm and 12.4 kg and live up to 20 years of age (Hay, 2006; Marriott, 2000).

Golden Snapper grow relatively quickly in their first few years before slowing down when they reach sexual maturity. Growth rates of 250 mm TL by age one, 500 mm TL by age seven and 600 mm TL by age ten have been recorded in the Northern Territory, with males taking ~5 years to reach maturity (~47 cm TL) and females ~ 8 years (~63 cm TL) (Hay, 2006). These authors also indicated that this species has a protracted spawning period from September to late April in the Northern Territory. It is thought that Golden Snapper undertake at least two major movements during their life cycle: an inshore migration as post-larvae or early juveniles from offshore spawning grounds and a subsequent offshore migration of sub-adult or mature fish (Kiso and Mahyam, 2003). While limited data exists on the precise movements of this species, long-term tagging programs on the Queensland east coast and in the Northern Territory suggest that movement is restricted to local scales regardless of size, with only limited numbers moving offshore (Welch et al., 2014).

Fishing pressure on inshore reef fish, especially Golden Snapper, has increased significantly in the Northern Territory, particularly in areas close to population centres (Grubert et al., 2010). Contributing factors include escalating fishing effort due to rapidly expanding recreational and fishing tourism sectors as the NT population increases in size. The increase in effort by these sectors has also been exacerbated by advances in technology (e.g. GPS, high quality sounders, and electronic motors) and accessibility of information (web forums, social media and accurate weather predictions) enabling fishing to be much more precise and targeted. Golden Snapper have also been shown to suffer from barotrauma with injury and post-release mortality proportional to capture depth (Northern Territory Government, 2016).

2.2. Stock structure

Research on the biological stock structure of Golden Snapper across Northern Australia suggests that many functionally separate adult populations are present at a scale of tens of kilometres, although the boundaries of the stocks are unknown (Saunders et al., 2016; Taillebois et al., 2021). Golden Snapper experience moderate to high harvest rates in some Australian fisheries (particularly those targeting adults of this late-maturing species), which can cause localised depletion given the fine scale of their population structure. Population structure in offshore waters is not known, but it is likely to be as complex as stocks found inshore.

The fine scale population structure of Golden Snapper makes assessing stocks at the biological level impractical with the data currently available. Therefore, the assessment of Golden Snapper stocks are presented at the assessment unit level in the Northern Territory:

1. The Greater Darwin Region
2. The Regional Northern Territory
3. The Gulf of Carpentaria.

2.3. Previous assessments

2.3.1. Greater Darwin Region

Golden Snapper were first assessed as depleted in 2011 using a NT wide stochastic Stock Reduction Analysis i.e., SRA (Grubert et al., 2013). The outputs indicated that Golden Snapper biomass and egg production in the Northern Territory were 20% and 10% of unfished levels, respectively and that there was a high (100%) probability that stocks were recruitment overfished and a high (99%) probability that harvest levels at that time were causing recruitment overfishing.

An SRA assessment in 2014 indicated that Golden Snapper in the NT had further declined with biomass and egg production estimated at 18% and 10% of unfished levels, respectively, and that there was a 100% probability that harvest levels at the time were causing the stock to remain overfished (Northern Territory Government, 2016).

An SRA assessment undertaken with data to 2017 was restricted to the 'Greater Darwin Region' to reflect the improved understanding of stock structure, which indicated that Golden Snapper exists as fine scale populations (Taillebois et al., 2021). The assessment encompassed the NT coast from Port Keats in the south to east of Croker Island in the north, and the Tiwi Islands (Saunders, 2018;Table 1; Figure 4), an area that encapsulates the majority of reef fishing effort from the recreational and FTO sectors (West et al., 2022). The assessment indicated that stocks remained recruitment overfished with a high degree of certainty that the harvest rate would continue to cause recruitment overfishing (Penny et al., 2018b).

2.3.2. Regional Northern Territory

The majority of fishing effort is concentrated around Darwin and fishing pressure is more diffuse in other areas of the Northern Territory. The 'Regional Northern Territory' assessment unit was identified in 2018 upon classifying the Greater Darwin Region as a separate unit based on stock structure research by Taillebois et al., (2021). This region encompasses the area from the WA border east to Port Keats, east of Croaker Island to the Gulf of Carpentaria, and all offshore waters north of 11°S. However, there was insufficient information available to confidently classify the status of this stock in 2018 (Penny et al., 2018a). The most recent assessment of this assessment unit was undertaken in 2020 (Saunders, 2020a) using a Catch-MSY model (Haddon, 2020). The assessment estimated that the 2019 biomass of Golden Snapper was 76% of unfished levels, indicating that it was unlikely that Golden Snapper in Regional Northern Territory were depleted and that recruitment was unlikely to be impaired. Fishing mortality was estimated to be 0.06, which is within sustainable limits indicating that the level of fishing mortality was unlikely to cause the stock to become recruitment impaired.

2.3.3. Gulf of Carpentaria

The Gulf of Carpentaria region has been identified as a separate assessment unit since 2014 but assessments were restricted to the Queensland jurisdiction (Saunders et al., 2014). In 2020, an assessment was conducted for the combined NT and Queensland component of

Gulf of Carpentaria (Saunders et al., 2020). This assessment applied Catch-MSY modelling (Haddon, 2020) and estimated that the 2019 biomass of Golden Snapper was 47% of unfished levels, suggesting that the biomass of this stock was unlikely to be depleted and that recruitment was unlikely to be impaired. Similarly, the fishing mortality in 2019 was 0.12 which approximated the target level, indicating that the current level of fishing mortality was unlikely to cause the stock to become recruitment impaired.

Table 1: Stock status outcome from the most recent fish stock assessments

Stock unit	Years of data	Assessment model	Stock status summary
Greater Darwin Region	1983 - 2017	Stochastic Stock Reduction Analysis (Lombardi and Walters, 2011)	Depleted (Penny et al., 2018a)
Regional Northern Territory	1970 - 2019	Catch-MSY (Haddon, 2020)	Sustainable (Saunders et al., 2020)
Gulf of Carpentaria	1945 - 2019	Catch-MSY (Haddon, 2020)	Sustainable (Saunders et al., 2020)

2.4. Overview of the Coastal Line Fishery

The Coastal Line Fishery (CLF) is a multi-sector fishery that spans the entire Northern Territory coastline, from the high water mark to 15 nm from the low water mark, which fishes for coastal reef species using predominantly hook and line methods. The fishery catches a wide range of coastal reef fish such as Black Jewfish, Golden Snapper, Grass Emperor, Coral Trout, cods and snappers. The majority of fishing activity in this fishery is concentrated around rocky reefs within 150 km of Darwin. To a lesser extent, fishing activity occurs adjacent to other popular coastal locations including Nhulunbuy and Borroloola (King Ash Bay).

2.4.1. Fishing methods

The principal fishing method used by all fishing sectors in the CLF is hook and line. This involves the use of weighted hand or reel lines (generally with baits or jigs). Recreational fishers and tourism clients mainly use rods and lines, while hand reels mounted to vessels (commonly known as deck winches) are used by commercial fishers. Commercial fishers are permitted to use drop lines that may contain up to 40 hooks and fish traps, but these gear types are rarely used. The hook and line methods employed in the CLF do not include fishing from a vessel that is under way and making way (e.g. fishing methods that involve trolling).

Hand lines are the simplest form of fishing; they consist of one or more baited hooks attached to a line, which is retrieved by hand. Hand lines are the most common traditional fishing method used by Aboriginal fishers.

2.4.2. Reef Fish Protection Areas

Five spatial closures (Reef Fish Protection Areas) have been implemented to aid in the protection and recovery of at-risk reef fish from overfishing. These protection areas are located at Melville Island, Bathurst Island, Lorna Shoal, Charles Point and Port Keats (Howland Shoal and Emu Reef) and apply to all fishing sectors that target reef fish. All reef protection areas are located within 250 km of Darwin.

2.4.3. Recreational and Fishing Tourism

The recreational and FTO sectors are managed through a combination of input and output management controls. These include spatial and temporal closures (e.g. temporary Reef Fish Protection Areas), personal and vessel possession limits (Table 2).

FTO licences must also submit daily catch and effort logbook data and access for FTO licences to target reef fish in the Western Zone is restricted to existing licenses granted before February 2015.

Table 2: Summary of current management controls for the recreational and fishing tourism sectors of the Coastal Line Fishery.

Management tool	Recreational	Fishing Tourism
General personal possession limit	15 fish per person	15 fish per person
Personal possession limits	3 Golden Snapper	3 Golden Snapper
Vessel limits	Vessels with 4 or less people on board, each person can take their personal possession limit Vessels with 5 to 7 people on board can take a maximum of 4 times the personal possession limit of 'at-risk' species Vessels with 8 or more people on board can take a maximum of 8 times the personal possession limit of designated 'at risk' species	Vessels with 4 or less people on board, each person can take their personal possession limit Vessels with 5 to 7 people on board can take a maximum of 4 times the personal possession limit of 'at-risk' species Vessels with 8 or more people on board can take a maximum of 8 times the personal possession limit of designated 'at risk' species
Catch and effort data	Recreational fishing surveys	Daily logbooks, submitted monthly
Licence restrictions	N/A	Reef fishing in the Western Zone is restricted to licences granted before the fishery restructure in 2015.
Closed areas	Reef Fish Protection Areas	Reef Fish Protection Areas

2.4.4. Coastal Line Fishery management controls

The commercial sector of the Coastal Line Fishery is managed as two separate zones using a combination of input and output based management controls. The Western Zone extends from the Western Australia border to Vashon Head on Cobourg Peninsula at the point of latitude 11° 07.516' south, longitude 131°59.650' east. The other zone extends east from Vashon Head to the Queensland border.

Regulations for the commercial sector primarily focus on managing the harvest of Black Jewfish, the primary target species for this sector. The controls used differ between the two zones of the fishery and management controls of specific relevance to Golden Snapper are presented in (Table 3). The main management control used to limit catch in the Western Zone of the fishery is an Individual Transferable Quota (ITQ) system based on a Total Allowable Commercial Catch (TACC) of Golden Snapper (4.5 t).

In the Eastern Zone, where there is significantly less fishing effort, the commercial sector is primarily managed through input based controls such as gear restrictions and limited entry.

Table 3: Summary of current management controls of specific relevance to Golden Snapper for the commercial sector of the Coastal Line Fishery.

Management tool	Western Zone	Eastern Zone
Limited Entry	52 licences, minimum quota	52 licences
TACC	4.5 tonnes Golden Snapper	-
Permitted gear	Vertical line (1-5 hooks) Cast nets (bait only) Scoop net and gaff Drop line (6-40 hooks)*	Vertical line (1-5 hooks) Cast nets (bait only) Scoop net and gaff Drop line (6-40 hooks)* Fish trap (5 per licence)*
Closed areas	Reef Fish Protection Areas	-
Catch and effort data	Daily logbook, submitted monthly	Daily logbook, submitted monthly
Pre-departure notice (includes prior landing)	1-12 hours prior to undocking, specifies time and location of departure point and landing	-
Catch disposal record	Within 1 day of unloading (electronic scales)	-

*-when fishing in waters from 2-15 nautical miles away from the coastline

2.4.5. Other commercial fisheries

The Demersal Fishery (DF) operates beyond the CLF boundary in the NT Fishing Zone. This fishery targets a multitude of species with catch predominantly comprising Saddletail, Crimson, Goldband snappers and Painted Sweetlips, with Golden Snapper making up a smaller portion of the fishery catch. Golden Snapper is also caught in small numbers as bycatch in the Timor Reef Fishery (TRF) and Offshore Net and Line Fishery (ONLF).

2.4.6. Aboriginal Coastal Licence

Under Section 183 of the *Fisheries Regulations 1992*, an Aboriginal person who is a member of a community or group in respect of which land has been granted to a trust for the benefit of Aboriginals entitled by Aboriginal tradition to the use or occupation of that land under the *Aboriginal Land Rights (Northern Territory) Act 1976* (C^{th}) may apply for an Aboriginal Coastal licence.

The Aboriginal Coastal Licence allows Aboriginal people to establish small-scale fishing enterprises as a 'stepping stone' for entry into larger scale commercial fishing business. Entry into larger scale business would be through normal means of purchasing an existing licence in a commercial fishery. The main species caught using these licences are Mullet, Blue Salmon, Queenfish, Milkfish and Trevally. In addition, licence holders operating in the Western Zone of the fishery are only permitted to sell five Golden Snapper per month.

2.4.7. Aboriginal traditional

The Aboriginal traditional fishing sector is entitled to use the resources of an area of land or water in a traditional manner. The *Fisheries Act 1988* states that "*Unless expressly provided otherwise, nothing in this Act derogates or limits the right of Aboriginal people who have traditionally used the resources of an area of land or water in a traditional manner to continue to use those resources in that area in that manner.*" This entitlement does not extend to engaging in commercial fishing activities without a licence.

2.5. Catch history

2.5.1. Recreational harvest

A Territory-wide (non-Aboriginal residents) recreational fishing survey 2018-2019 showed that, excluding Barramundi, Golden Snapper were the most common fish species caught by the recreational fishers with an estimated 65,000 fish landed (12% of the recreational catch), down from a comparable survey in 2009-2010 reporting an estimated 80,000 fish caught. In both surveys 53% were reportedly released, however, due to known susceptibility to barotrauma post-release mortality is likely significant. The majority (>70%) were caught in the Darwin Region. Yearly surveys of selected boat ramps in the Greater Darwin Region from 2014-2017 also indicated that Golden Snapper was the most commonly caught reef fish over the period.

2.5.2. Fishing Tourism Operator harvest

Log book data has indicated a decline in catches of Golden Snapper by the Fishing Tour Operator sector in recent years, particularly in 2020 and 2021, after a peak of 18,000 fish in 2017 (Figure 1). It is likely that travel restrictions related to the COVID-19 pandemic had a negative impact on the FTO sector during 2020 and 2021.

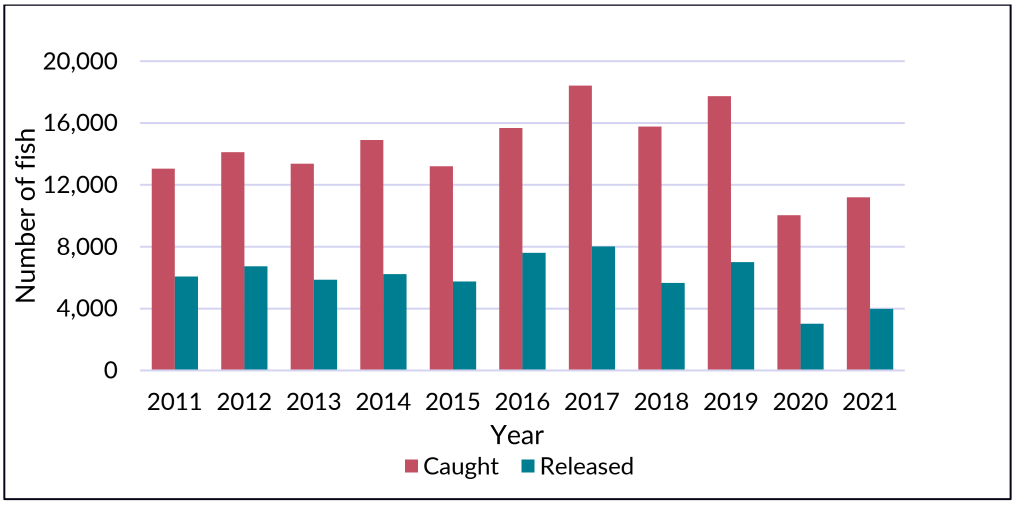


Figure 1: Number of Golden Snapper caught and released by Fishing Tour Operators in the Northern Territory from 2011 to 2021.

2.5.3. Commercial harvest

A total allowable commercial catch limit of 4.5 tonnes of Golden Snapper per year was introduced for CLF licenses in the western zone in 2015. Black Jewfish is the target species of the commercial component of the Coastal Line Fishery, with Golden Snapper only retained as an incidental by-product, accounting for just 2.6% of the total catch in 2021. Golden Snapper is also landed as by-product by other commercial fisheries (Demersal, Timor Reef and Offshore Net & Line fishery), predominantly outside the Great Darwin Region (Figure 2).

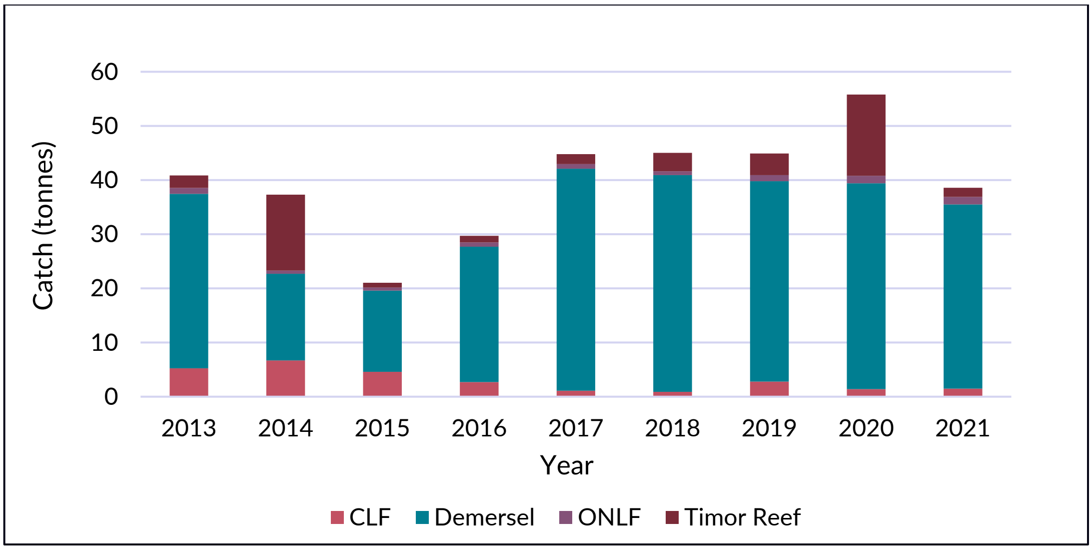


Figure 2: Total Golden Snapper catch by Northern Territory managed commercial fisheries from 2013-2022, which averages 40 t per annum.

2.5.4. Aboriginal traditional harvest

Golden Snapper harvest by the Aboriginal traditional sector is poorly quantified in the NT and there are no contemporary estimates of Golden Snapper harvest available for this assessment. A modified creel survey was undertaken in 2001, which estimated fishing effort and harvest by Aboriginal fishers across northern Australia (Henry and Lyle, 2003). Within the survey Golden Snapper were reported as "sea perch/snappers in a species complex that included other *Lutjanus* species. The survey estimated the Aboriginal sector harvested 27,600 "sea perch/snappers" in the Northern Territory in 2001 (Henry and Lyle, 2003).

2.6. Stock assessment models

Three stock assessment models are considered for the assessment of Golden Snapper in the Northern Territory.

1) Stock Synthesis
2) Stochastic Stock Reduction Analysis (SRA)
3) Catch – Maximum Sustainable Yield (Catch-MSY)

The choice of model used on each assessment unit depends on the types of input data that is available, which may include:

- Catch and other removals from the stock.
- An index of stock abundance (typically the Catch Per Unit Effort – CPUE).
- Annual length composition data.
- Annual age composition data.

2.6.1. Stock Synthesis

The 2021 assessment of Golden Snapper in the Greater Darwin Region applied an age- and size-structured population dynamics model implemented in the generalised stock assessment software package, Stock Synthesis (Methot, R. D. et al., 2024). Stock Synthesis is an integrated model where a population model is fitted to a variety of data types to determine the number of Golden Snapper in each year and each age group. Stock Synthesis has a population sub-model that simulates a stock's growth, maturity, fecundity, recruitment, movement, and mortality processes, an observation sub-model estimates expected values for various types of data, a statistical sub-model characterizes the data's goodness of fit and obtains best-fitting parameters with associated variance. Stock Synthesis can analyse data by fleet/sector (i.e. area with different gear selectivity or stock vulnerability) and can estimate selectivity from size composition data. The population dynamics model and the statistical approach used in fitting the model to various data types are given in the Stock Synthesis technical documentation (Methot, R. D. et al., 2024).

2.6.2. Stock Reduction Analysis

Stock Reduction Analysis (SRA) is a population dynamics model consisting of life history parameters that describe the underlying production and carrying capacity of a population over time (Walters et al., 2006). Inputs include long term catch history and a time series index of abundance with the option of including age/length composition data (Lombardi and Walters, 2011). Stochastic SRA uses *MSY* (Maximum Sustainable Yield) and U_{MSY} (exploitation required to achieve *MSY*) as leading parameters for the assessment.

The model simulates changes in biomass by subtracting estimates of mortality and adding new recruits, where the new recruits are a function of the current stock size and the leading parameters. Stochastic SRA provides probability distributions of population parameters over time, given alternative hypotheses about unfished recruitment rates and variability around the assumed stock-recruitment relationships. These distributions are generated by conducting a very large number of simulation trials and retaining those sample trials for which the stock would not have been driven to extinction by historical catches. A detailed description of Stochastic SRA can be found in Walters et al. (2006) and a summary in Grubert et al. (2013).

2.6.3. Catch-MSY model

Catch-MSY method evolved from the stock reduction analyses of Kimura and Tagart (1982), Kimura et al. (1984), and eventually Walters et al. (2006) but can be implemented for stocks that are relatively data poor. Catch-MSY is a 'model-assisted' stock assessment method (Martell and Froese, 2013) that only requires a time series of catch data. The underlying stock dynamics are described by a simple biomass based Schaefer production model with parameters '*r*' (the population growth rate), and '*K*' (the population carrying capacity or unfished biomass). The model computes ratios of the initial and final catches relative to the maximum catch to set up arrays of potential values for the initial and final depletion levels. It also set up the potential range of *r* and *K* values which can be modified by the user. The method randomly selects initial pairs of *r*-*K* values and sequentially steps through the years moving the population dynamics forward and subtracting the catches. A large number of iterations of the Catch-MSY model is run to generate 100,000s of possible stock reduction trajectories (Haddon, 2020).

The Catch-MSY model is implemented using the 'datalowSA' package in R (Haddon, 2020). Catch-MSY provide estimate of harvest rate to indicate fishing pressure on the stock. The harvest rate (H, annual mortality rate) is converted to fishing mortality (F, instantaneous mortality rate) using the equation (Simpfendorfer et al., 2005):

$$H = 1 - \exp(-F)$$

Using the average estimate of the *r*-*K* pairs from successful trajectories, an estimate of reference points such as the virgin stock biomass (B_0) and maximum sustainable fishing mortality (F_{MSY}) can be derived. Catch-MSY models do not provide an estimate of F_{MSY} so a harvest of 50% of B_0 is assumed as its equivalent (Tsikliras and Froese, 2019). B_0 and F_{MSY} can be used to visualize and interpret how the history of catches from the fishery have impacted the stock being assessed. The status of stock position can be determined by the stock biomass (*B*) and fishing mortality (*F*) in the last year of the time series in relation to the reference points in order to determine the stock status. However, caution should be used in stock biomass trends from Catch-MSY as there is greater uncertainty as a consequence of using limited information to inform the model.

2.7. Criteria for determining the stock status

2.7.1. Reference Points

The state of fish stocks are classified based on two indicators which are:

1) Biomass (*B*) of the fish stock relative to unfished levels

2) Fishing Mortality (*F*) relative to *F* at the Maximum Sustainable Yields (F_{MSY}).

Reference points are set from these indicators such that a 'sustainable' stock would have *B* that is not recruitment overfished and *F* is not high enough to drive the stock in the direction of recruitment overfishing. The reference points used for the current assessment are:

1) $\boldsymbol{B_{20\%}}$ - 20% of unfished biomass ($B_{20\%}$) is point below which it is assumed that the recruitment to a stock is impaired (recruitment overfished) and is a widely used as the default for the 'Limit Reference Point' (Haddon et al., 2012; Klaer et al., 2012).

2) $\boldsymbol{F_{MSY}}$ – Fishing mortality at Maximum Sustainable Yield (F_{MSY}) is assumed to be the point beyond which fishing pressure is not sustainable and would drive the stock in the direction towards 'recruitment overfishing'.

2.7.2. Stock Status

The reference points $B_{20\%}$ and F_{MSY} are used in a phase plot to determine the status of fish stocks (Figure 3). The relative stock biomass for the most recent year (B_{2021}/B_0)[1] is compared with $B_{20\%}$ to determine whether the stock is 'recruitment overfished'. The fishing mortality from the same assessment year (F_{2021}) is compared with the level at 'Maximum Sustainable Yield', F_{MSY} to determine whether 'recruitment overfishing' is occurring i.e., F_{2021}/F_{MSY}.

[1] The term 'B_0' represents the biomass of the stock at unfished level (virgin biomass), 'B_{2021}' indicates the biomass in year 2021 and $B_{20\%}$ is the biomass at 20% of unfished levels.

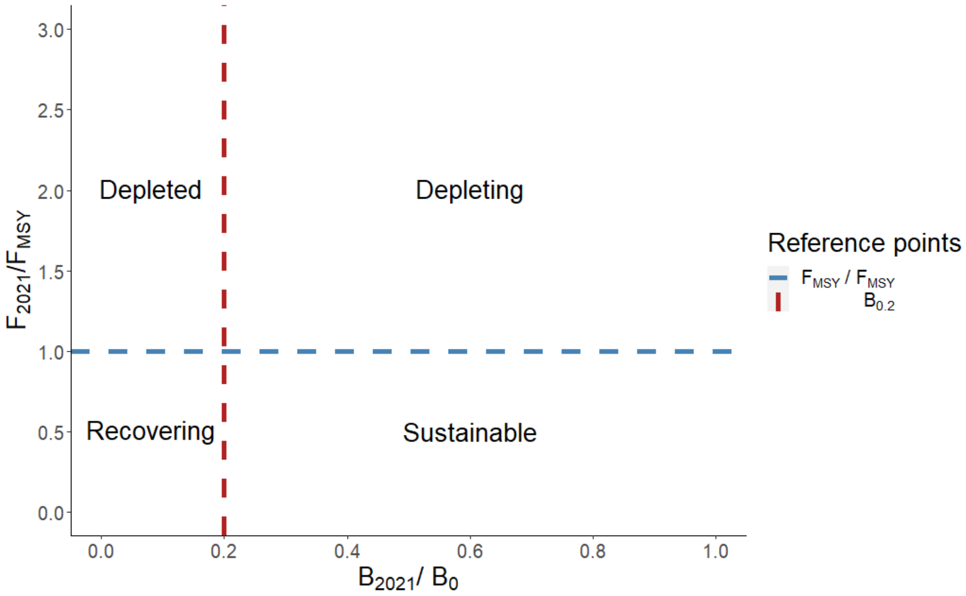


Figure 3: Phase plot showing the criteria used for determining the stock status.

3. Greater Darwin Region Assessment

The Greater Darwin Region encompasses the coastal and nearshore waters from Port Keats to east of Croker Island (Figure 4). The majority of fishing activity in this assessment unit is concentrated around rocky reefs within 150 km of Darwin. This assessment unit likely encompasses multiple biological stocks, however, as these populations likely receive similar (relatively high) fishing pressure they have been grouped to a single assessment unit.

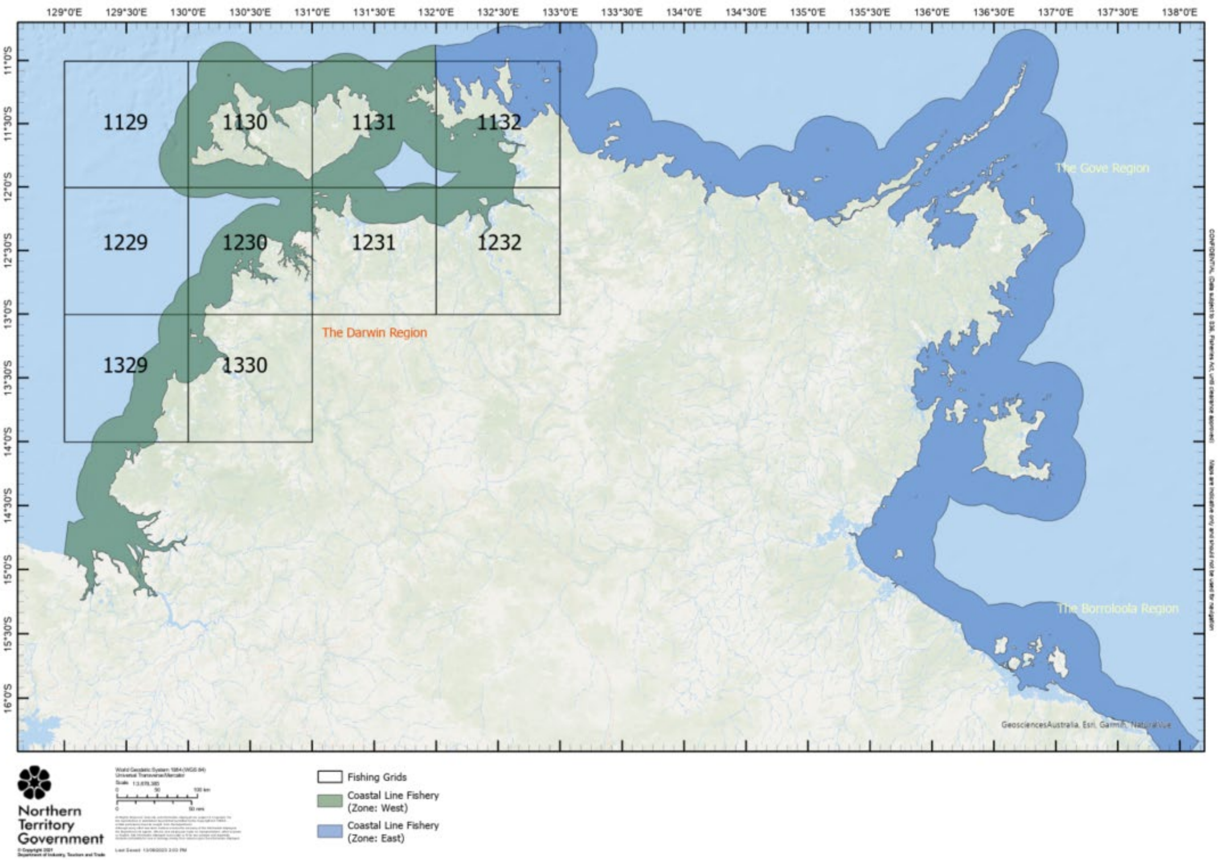


Figure 4: Greater Darwin region assessment area, spatial grids represent the area from which the commercial and fishing tourism data were derived. The dark green and dark blue shaded region represents the boundaries of the Western Zone and Eastern Zone of the Coastal Line Fishery.

3.1. Data inputs

The Greater Darwin Region assessment spans from 1970 to 2021 and includes total removals by the commercial, Fishing Tour Operators (FTO) and recreational sectors (Figure 5). The assessment also includes FTO CPUE as an indicator of abundance, and length and age composition from the FTO sector.

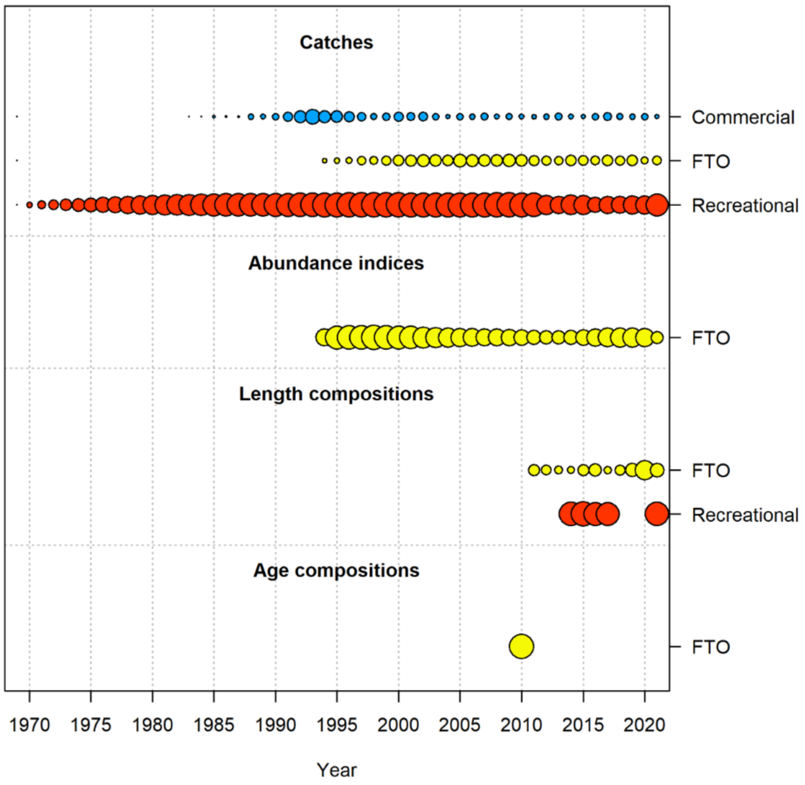


Figure 5: Summary of data sources used for the Greater Darwin Region assessment unit. Circles are scaled relative to maximum within each type. Circles are proportional to total catch for catches, to precision for abundance indices and to total sample size for age/length composition.

3.1.1. Catch history by sector

Recreational sector

The recreational sector harvests the largest portion of Golden Snapper in the Greater Darwin Region (Figure 6). Determining the total catch from this sector presents a challenge as there is no requirement for recreational fishers to report their catch.

Regular recreational fishing surveys provide estimates of Golden Snapper catch by recreational fishers in the NT. NT wide recreational surveys have been conducted in 2000, 2009-10 and 2018-19, and Darwin based surveys have been undertaken in 2014, 2015, 2016 and 2017 (Coleman, 1998; Errity et al., 2022; Matthews et al., 2022, 2019a, 2019b; West et al., 2022, 2012).

Annual catch for intervening years was reconstructed from 1970 until 2021 by multiplying per capita fish caught with the number of fishers. Number of fishers in each year is estimated by multiplying the NT population with participation rates. The participation rates and per capita fish caught were sourced from NT recreational survey reports but a linear interpolation was applied for missing years. The reconstructed catch is converted from total numbers to weight by applying the average weight of fish as recorded through FTO observer programs.

Fishing Tour Operator (FTO)

Given that both the fishing method and the spatial distribution of effort for the FTO and recreational sectors is analogous, FTO catch rates are used as a proxy to reflect the interaction of both these sectors with Golden Snapper in the Greater Darwin Region. The FTO sector reports their catch and effort via a logbook system, with records available since

1994 (Figure 6). Catch is reported as numbers, which is converted to a weight based on the average weight of fish estimated from FTO observer trips since 2011. Further, the annual catch is adjusted for marginal reporting errors (possible over or under reporting) as validated through the FTO observer programs. The program also provides length composition data which can be considered reflective of both recreational and FTO sectors given the similarity of gear selectivity patterns.

Commercial

Commercial catch of Golden snapper in the Greater Darwin Region is limited, contributing 6% of the total harvest. The Coastal Line Fishery licences contribute the majority of the commercial catch, with minor contributions from the Offshore Net and Line, Demersal and Coastal Net fisheries (Figure 6). Commercial catch by licenced operators in the Coastal Line Fishery is managed under a restrictive TACC of 4.5 t. Commercial catch data is available from logbook records since 1983 where the peak removals have been from the Coastal Line Fishery using hook and lines (1992-2002, 13.2 t/annum) and the Demersal Fishery using midwater/bottom trawls (1991-1994, 13.5 t/annum).

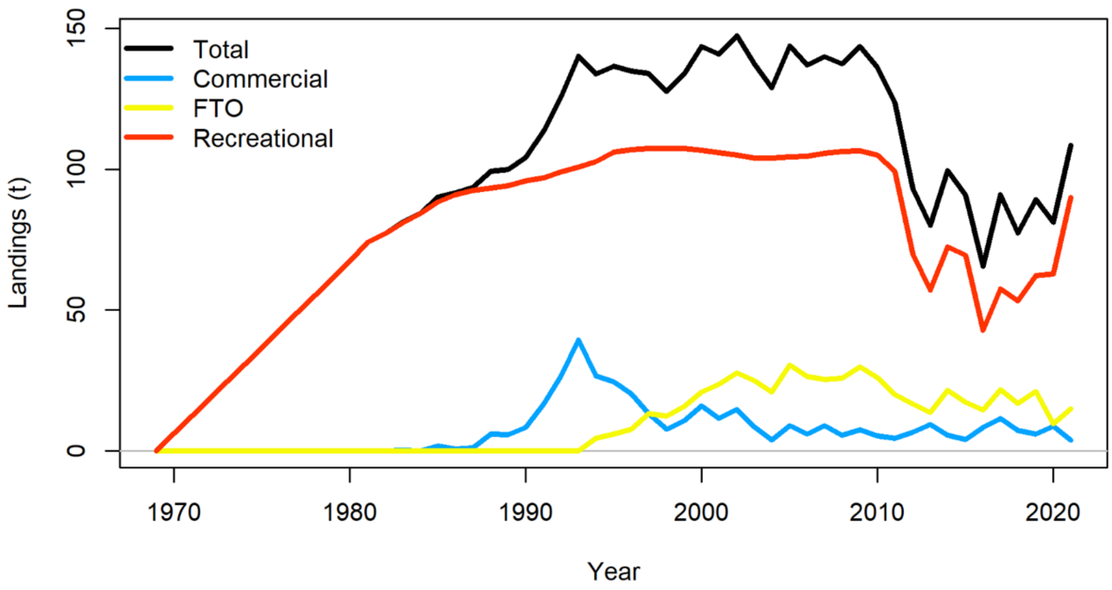


Figure 6: Annual estimated harvest (retained and discarded catch) from commercial, recreational and FTO sectors between 1970 and 2021. The commercial component include harvest from multiple fisheries but predominantly from the Coastal Line Fishery.

3.1.2. Abundance index

The trend in annual standardized Catch Per Unit Effort (CPUE) is often used in stock assessments as an abundance index to indicate the number of fish caught in a specified time interval (aka catch rate). In the absence of fishery-independent estimates of relative abundance, CPUE data were extracted from daily logbook records from the FTO sector. However, nominal CPUE is highly influenced by factors such as the location, time, fisher behaviour and fishing efficiency which adds temporal and spatial dependency (Campbell et al., 2017). To remove such effects, CPUE is standardised before use in stock assessment models.

CPUE standardisation

Previous stock assessments of Golden Snapper have used the 'spatial averaging' technique to address the non-random search behaviour of fishers (Saunders, 2018). This is achieved by ensuring all spatial grids (60 NM X 60 NM) have catch rates as if they would reflect a random search behaviour by fishers where the fish population is uniformly distributed throughout the spatial grids considered for the assessment. Contemporary practice uses regression techniques such as Generalized Linear Model (GLM) or Generalized Additive Model (GAM) to remove temporal and spatial dependency in the data (Campbell et al., 2017). In the current assessment, a GLM is used to standardise catch rates from the FTO sector. Spatial averaging has also been applied to FTO catch rates to assess the consequence of adopting a GLM modelling approach.

Spatial averaging

To prepare for spatial averaging, annual CPUE data (No./linehr) for each (60 x 60 NM) fishing grid were entered into a spread sheet with a column for each year and a row for each grid cell that could have been fished. Empty grids (where no fishing had occurred) were filled as follows:

- Grids for years prior to any fishing occurring were back-filled with the highest CPUE recorded during the years when fishing began in those grids.
- Grids where fishing had occurred, but were no longer being fished were forward-filled with the last recorded CPUE.
- Empty grids in-between fished years were filled with the difference between the closest years CPUEs.

Catch rates for all grids within each year were then averaged to generate a spatially averaged CPUE time series. The rationale behind the filling of empty cells prior to fishing is that each grid would have supported enough of the target species for catch rates to have been at least as high as the highest CPUE after initial exploration (Figure 7).

Generalized linear modelling

The GLM based standardisation technique is a linear regression method where temporal and spatial dependency in the data can be removed by adding such components as explanatory variables in the model (Maunder et al., 2020). They can also deal with relatively high proportions of zeros in the response variable which is common in fisheries data, particularly for species that are depleted or not targeted. In the current assessment, the CPUE of Golden Snapper caught (response variable) from the FTO sector was considered for GLM standardisation to reflect the abundance of fish population from 1994 until 2021. The covariates considered for catch standardisation are Year, Month and Grid (spatial unit) associated to a fishing session. To ensure a good balance of data, covariates with less than 20 records within a level were removed to prevent problems associated with small sample size before fitting the GLM model (Zuur and Ieno, 2021).

Several models were developed and tested using a range of probability distributions (normal, poisson, negative binomial, zero inflated models, tweedie and hurdle models). Based on the outcome of Akaike Information Criteria (AIC), dispersion test, zero inflation test and distribution of residuals around the fitted model, a Zero Altered Gamma (ZAG) model with a 'log link' was selected for predicting the annual trend in CPUE while keeping all other covariates constant (Appendix B). The ZAG have a zero inflated component (Bernoulli GLM) with Year, Month and Grid as covariates and a Gamma GLM component with Year, Month and Grid as covariates. The standardised CPUE per fishing session from 1994 to 2021 (Figure 7) is used as an index of abundance for the scenarios considered in stock assessment.

Figure 7: Annual abundance index used for stock assessment after standardisation using the 'Spatial Averaging' technique and 'Generalized Linear Modelling' technique.

3.2. Length compositions

Length composition data were collected from observer trips undertaken on FTO vessels and recreational boat ramp surveys in the Greater Darwin Region between 2011 and 2021 (Figure 8, Figure 9). There is considerable spatial and temporal overlap between the FTO and recreational sectors and the selectivity pattern of the gears used by each sector are likely very similar as both employ hook and line.

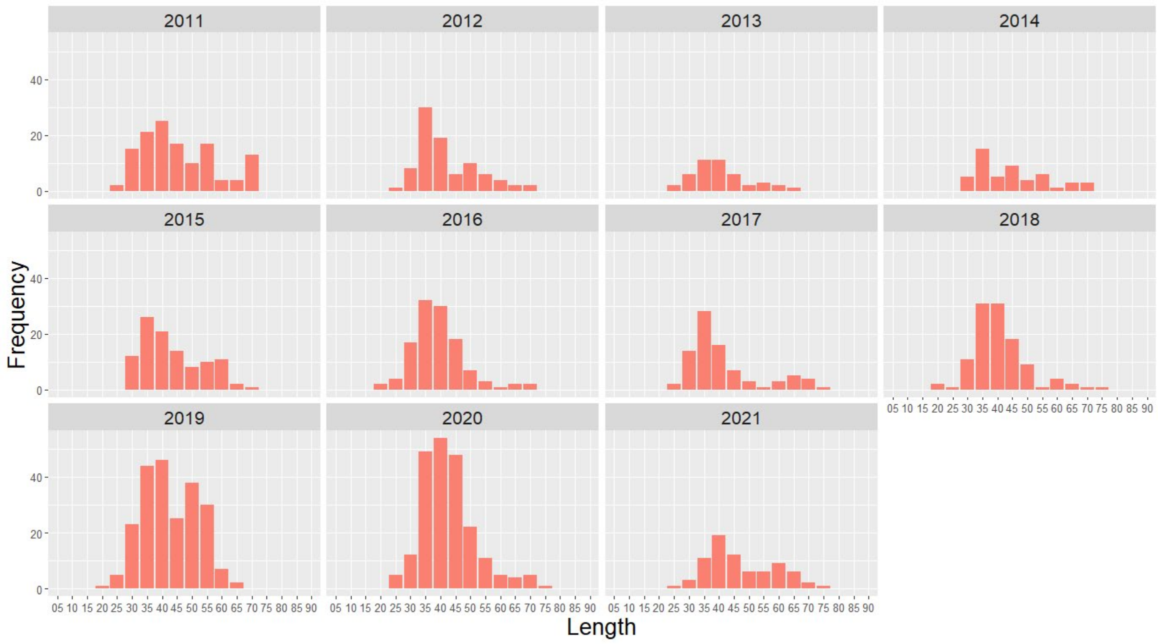


Figure 8: Annual length compositions of Golden Snapper from observer trips conducted in the FTO sector between 2011 and 2021.

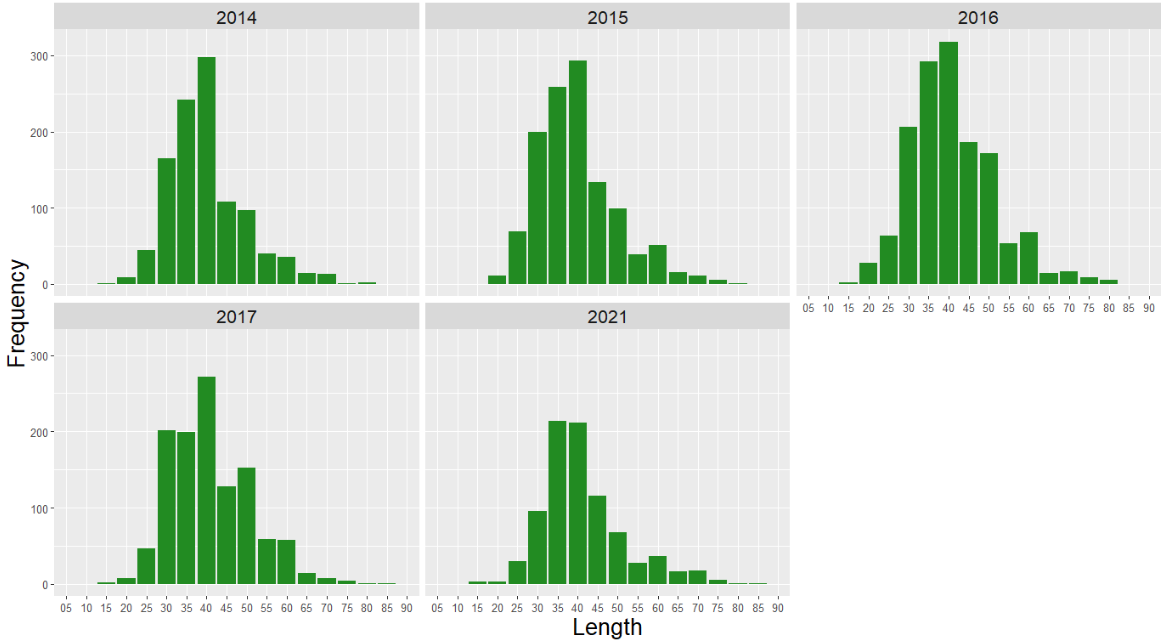


Figure 9: Annual length compositions of Golden Snapper from boat ramp recreational fisher surveys conducted between 2014 and 2021.

3.3. Age compositions

Age information for Golden Snapper in NT waters is limited. Age data has been collected in the Greater Darwin Region during the mid-2000s and during monitoring in 2010. The age data collected in mid-2000s was excluded as the sampling was spatially restricted and not considered representative of the fishery in the Greater Darwin Region due to the spatial bias (Saunders, 2020b). The 2010 monitoring study (unpublished internal report) provides age composition data along with region-specific biological parameters that are used for the current assessment. The ageing samples were collected from recreational and FTO's sectors, as well as several field surveys. For modelling purposes, it is assumed that the age composition data collected in 2010 is representative of the FTO sector. The age composition profile for 2010 shows that all age groups above or equal to age=2 are fully vulnerable to fishing (Figure 10). This indicates that individuals become vulnerable to fishing before first spawning given that 50% of the population mature at age ≥5.

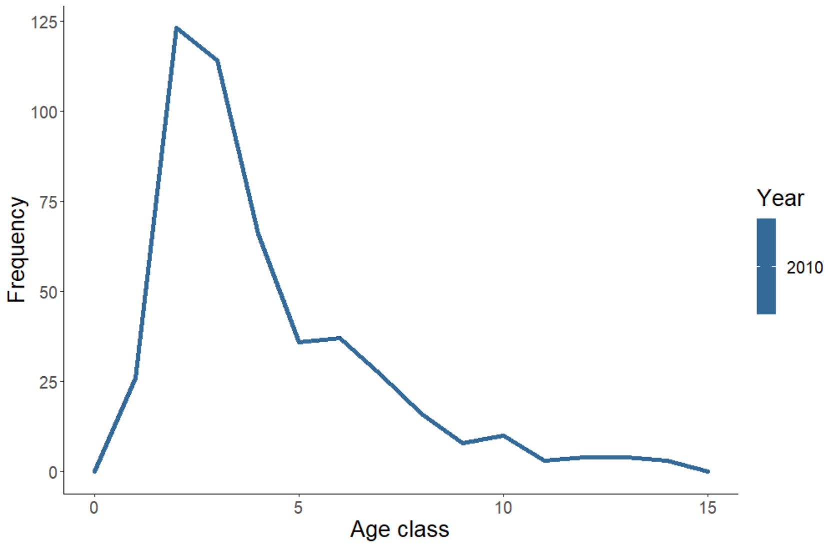


Figure 10: Age composition of Golden Snapper from the Greater Darwin Region in 2010

3.4. Stock Synthesis

Stock Synthesis models were implemented using the SS-Data Limited (SS-DL) tool (Cope, 2023). The interface in SS-DL allows implementation of several standard data-limited assessment methods all in one modelling framework where additional data can be added as it becomes available. The tool builds Stock Synthesis files for provided data and life history information. It produces full plots and tables for each model run via the ‘r4ss’ R package (Taylor et al., 2021) and additional screen output for interpretation.

3.4.1. Model Structure

The underlying model in Stock Synthesis use a single area, two sex model (sex ratio of 1:1) with population reaching a maximum age of 22 years. The biological parameters is assumed same for both sexes as sex specific values and associated age or length composition data are not available for this stock in the Greater Darwin Region (see Table 4).

The growth, maturity, recruitment and mortality of the population was modelled using an annual time step. The growth and maturity parameters are pre-specified as there is a paucity of age and length composition data available to estimate these parameters within the model. The pre-specified values are sourced from unpublished reports based on extensive field-based research in the Northern Territory between 1995 and 2010.

Growth was assumed to follow the von Bertalanffy growth model and the parameters (including allometric length-weight relationship) were consistent with those used in the previous stock assessment of Golden Snapper (Saunders, 2018). Maturity is modelled as a logistic function, with 50% maturity pre-specified at 56.5 cm so the age at maturity is 4 years. Fecundity-at-length is assumed to be proportional to weight-at-length.

Recruitment to the stock follows a Beverton-Holt stock-recruitment relationship, parameterised by the average recruitment at unexploited spawning biomass, R_0, and the stock recruitment steepness parameter, h, was fixed at 0.7 (Section 3.5.5). An estimate of natural mortality (*M*) for the stock in Greater Darwin Region is not available. However, an investigation across Northern Australia indicate that *M* is between 0.146 and 0.590 (Cappo et al., 2013). A fixed value of *M*=0.255 is used in the reference model but the sensitivity around this value has been explored in other scenarios (Section 3.5.5).

3.4.2. Input data

The major data components used in the model for Golden Snapper assessment are the annual catch, abundance index (standardised CPUE), length and age composition data (Table 5).

3.4.3. Fleets

The model used three fleets: one for all commercial fisheries combined, a second for the FTO sector and a third for the recreational sector. The selectivity of the commercial fleet was assumed to be ‘logistic’ with pre-specified values (Table 6). Length composition data are available for the FTO and recreation fleets so the selectivity parameters were estimated within the model. Similar priors were provided for the selectivity of FTO and recreational fleets noting that the primary fishing gear in both fleets is ‘Hook and Line’.

Table 4: Life history and population parameters for the assessment of Golden Snapper in the Greater Darwin Region (Section 3.8).

Acronym	Description	Input Parameters	Estimated or Pre-specified
R_0	Virgin recruitment	Exponent of 12	Estimated, initial value with no prior
h	Steepness	μ=0.7	Pre-specified
M	Natural Mortality	μ=0.255	Pre-specified
L_{inf}	Asymptotic length	μ=67	Pre-specified
K	Von Bertalanffy Growth Parameter	μ=0.28	Pre-specified
t_0	Length at age 0	μ=0	Pre-specified
CV_{young}	Coefficient of variation in length of young individuals (juveniles)	0.1	Pre-specified
CV_{old}	Coefficient of variation in length of old individuals (adults)	0.05	Pre-specified
r_σ	Recruitment deviations	0.5	Estimated with SS-DL options and bias ramp adjustment
W-L a	Intercept for length-weight relationship	0.00003	Pre-specified
W-L b	Coefficient for length-weight relationship	2.83	Pre-specified

Table 5: Input data in SS-DL for the assessment of Golden Snapper in the Greater Darwin Region.

Data Type	Description	Fleets
Catch Time Series	Total removals by each sector from 1970 to 2021	Commercial, FTO & Recreational sector
Abundance Index	GLM standardised catch rate from 1994 to 2021	FTO sector
Age composition	Age composition data from 2010	FTO sector
Length composition	Length composition data from 2011 to 2021	FTO sector
Length composition	Length composition data from 2014 to 2021	Recreational sector

Table 6: Selectivity parameters are estimated or pre-specified based on the availability of length data.

Fishery	Type of selectivity	Length at 50% selectivity	Length at 95% selectivity	Estimated or Pre-specified
Commercial	Logistic	40 cm	50 cm	Pre-specified
FTO	Logistic	30 cm	36 cm	Estimated using priors in phase 2
Recreational	Logistic	30 cm	36 cm	Estimated using priors in phase 2

3.4.4. Model tuning

Model tuning is an iterative reweighting of input and output CVs or input and effective sample sizes for ensuring that the expected variation of the different data streams is comparable to what is provided as input (Pacific Fishery Management Council, 2019). Tuning was applied to the CVs in standardised CPUE and sample sizes of age/length composition data. This is done by:

- **CVs for CPUE**: the error for relative abundance indices were set to the estimated standard errors to the standard deviation of a loess curve fitted to the GLM standardised CPUE.
- **Recruitment bias ramp adjustment**: The magnitude of bias-correction depends on the precision of the estimate of recruitment. Time-dependent bias-correction factors were estimated following the approach of Methot and Taylor (2011).

An automated iterative tuning procedure was used for the remaining adjustment. For the marginal age and length composition data:

- **Multiply the stage 1 (initial) sample size of marginal age/length composition data**: Sample sizes were iteratively adjusted using a multiplier until the effective sample sizes in the model are similar after Stage 2 tuning (Punt, 2017).
- **Stage 2 tuning for model data weighting**: Francis adjustment (Francis 2011) was applied via SS-DL to adjust relative weighting across CPUE, age and length composition data.
- Repeat steps, until all are converged and stable (proposed changes <1%).

The Stock Synthesis model was tuned to ensure that the final model is biologically sensible, fits appropriately with the abundance index data with additional diagnostic checks for its convergence, goodness of fit, model consistency and prediction skill (Carvalho et al., 2021). This procedure constitute current best practices for tunning assessment.

3.4.5. Sensitivity tests

Additional model runs were undertaken to determine the sensitivity of the results to some of the assumptions and data inputs considered in the assessment. These include,

- **Natural mortality (*M*)** – In general, *M* represents all mortality that is not attributed to the fishery e.g., predation, starvation, disease, senescence (Maunder et al., 2023). Golden Snapper may live over 20 years (Hay, 2006) and methods based on maximum age (20-25 years) indicate the *M* is likely between 0.21-0.31 (Hamel et al., 2015; Then et al., 2015). The base value of *M* used in the reference model for this assessment was estimated at *M*=0.255 using ‘FishLife’ via ‘The Natural Mortality Tool’ of NOAA (Cope and Hamel, 2022; Thorson et al., 2023). To understand the uncertainty of biomass towards the assumption of *M*, sensitivity of the model was tested for relatively low (0.255), medium (0.355) and high (0.455) *M* values.
- **Steepness (*h*)** – *h* is the fraction of recruitment from a population obtained when the spawners are at 20% of the virgin level (Lee et al., 2012). *h* technically ranges from 0.2 to 1, with the value determining the shape of stock-recruitment relationship (Beverton-Holt stock recruitment model, Beverton and Holt, 1957). *h* is usually very difficult to estimate (Lee et al., 2012) so it is common to pre-specify this parameter with externally-driven values (or meta-analyses on ecologically similar species) and run sensitivity tests (Punt, 2023; Tagliarolo et al., 2021). An exploration in the ‘FishLife’ package in R shows a wide range of values for Golden Snapper but with highest probability around *h*=0.7. To understand the uncertainty of biomass towards

the assumption of h, sensitivity of the model was tested for low (0.5), medium (0.6), high (0.7) and very high (0.8) values.

- **Asymptotic Length (L_∞) –** L_∞ is the length that the fish of a population would reach if they were to grow indefinitely. The previous assessments assumed a value of 67 cm which has been adopted for the reference model in this report. However, a field based research study in NT Fisheries between 1995-2000 shows the 'asymptotic length' may be 76 cm (unpublished internal report, NT Fisheries) and the length composition analysis have recorded samples up to 80 cm (Hay, 2006). Although L_∞ can be estimated within a model when sufficient data is available, the paucity of conditional age-at-length data limits the estimation of this parameter within the current model.
- **CPUE standardisation technique** – Generalized Linear Modelling (GLM) is a contemporary regression technique used for standardising CPUE index for stock assessment. Previous stock assessments of Golden Snapper in the Greater Darwin Region from 2011 use a 'Spatial Averaging' technique to standardise CPUE i.e., to remove the effect of non-random choice of spatial sub grids for fishing by the FTO sector. To understand the uncertainty of biomass as a consequence of replacing the standardisation technique, sensitivity of the model was tested by running a Stock Synthesis model with CPUE standardised using the 'Spatial Averaging' technique.

To address the sensitivity of the reference model towards the choice of natural mortality, steepness, asymptotic length and CPUE standardisation technique, a total of 9 scenarios were explored to understand the uncertainty of biomass and stock status in 2021 (Table 7).

Table 7: Scenarios considered for assessment of Golden Snapper in Greater Darwin region. The cells shaded in grey are the criteria that are different from the reference model.

Scenarios	*M*	*h*	L_∞	CPUE Standardisation
Scenario 1	0.155	0.7	67	GLM technique
Scenario 2 -Reference model	0.255	0.7	67	GLM technique
Scenario 3	0.355	0.7	67	GLM technique
Scenario 4	0.455	0.7	67	GLM technique
Scenario 5	0.255	0.5	67	GLM technique
Scenario 6	0.255	0.6	67	GLM technique
Scenario 7	0.255	0.8	67	GLM technique
Scenario 8	0.255	0.7	76	GLM technique
Scenario 9	0.255	0.7	67	Spatial Averaging technique

3.5. Stock assessment outcome

The stock assessment estimates the female spawning stock biomass of the population for 1970 to 2021. For the Greater Darwin Region 'biomass' refers to the female spawning stock biomass.

The depletion trajectory shows that the biomass has been declining since the 1970s (Figure 11a). There was a small increase in relative biomass around 2000 possibly influenced by high recruitment in 1995 (see Figure 14). It is to be noted that the increase also coincides with the first year of the abundance index and there may be some population adjustment in response to that time series. The biomass declined from 35% unfished levels in 2001 to 10% unfished levels in 2015 (Figure 11a). From 2016, an increasing trend of biomass is observed in the model indicating the estimated biomass in 2021 is 21% of unfished biomass with confidence intervals between 13% and 29% of unfished biomass (Figure 11a).

The model also predicted an increasing trend in fishing mortality until 2012 where fishing pressure was estimated at around four times the level required to sustain Maximum Sustainable Yield (with mean relative fishing mortality of approximately 3.06 from 2011 to 2015). A significant drop in fishing mortality was observed from 2015, with relative fishing mortality averaging 1.89 from 2016 to 2021 (Figure 11b). The fishing mortality determined by the model in 2021 is estimated at 2.1, with the confidence interval ranging from 1.35 to 2.82, relative to the MSY levels.

Management actions introduced in 2015 (e.g. reduced possession limit, vessel limits, Reef fish protection areas and education campaigns) may have supported increases in Golden Snapper biomass, although further evidence is needed to support this. Reduced FTO catch from 2019 to 2021 as a result of COVID-19 travel restrictions may have also impacted the predicted fishing mortality.

A phase plot of biomass (relative to unfished levels) against fishing mortality (relative to F_{MSY} levels) shows that the stock is positioned in a ‘Depleting’ status (Figure 11c). It is important to note that the plot indicates 50th percentile values that do not capture the full uncertainty of the ‘Stock Status’.

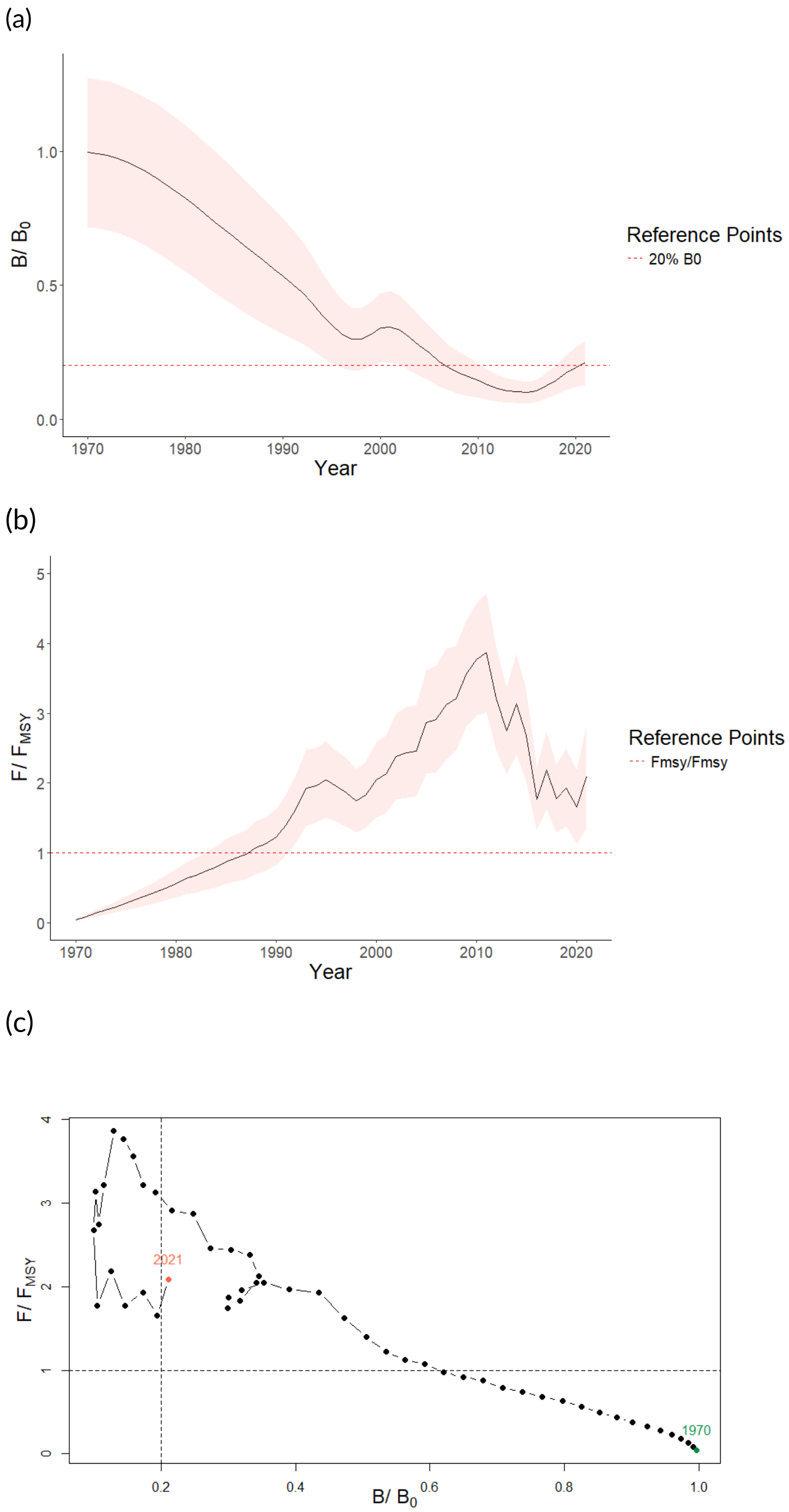


Figure 11: Stock assessment outcome for Golden Snapper in the Great Darwin Region (a) the estimated time series of relative biomass level with 95% confidence intervals (b) trend of fishing mortality relative to the level of 'Maximum Sustainable Yield (MSY) with 95% confidence intervals (c) phase plot showing the status of Golden Snapper in the Greater Darwin Region as 'Depleting' (Figure 3)

3.5.1. Model fits

The life history profile contributing to the growth and maturity is illustrated in Figure 12a, and Figure 12b. The model fits to CPUE, age and length composition data are illustrated in Figure 13. Recruitment estimated within the model and the bias ramp adjustment applied is illustrated in Figure 14.

3.5.2. Sensitivity analysis

Natural mortality

Natural mortality is the most influential and challenging parameter to estimate in fish stock assessments (Lee et al., 2011). The final biomass depletion in 2021 varies significantly across the range of *M* values explored (Figure 15). The likelihood profiling indicates there are significant conflicts in the data with respect to *M* and estimation of this parameter would be considered uninformative in the context of these conflicts (Appendix, Figure C 5).

As the value *M* increases the assessment unit becomes progressively less depleted to the point where a value of *M* = 0.455 (Scenario 4) results in a median depletion of 58% of unfished levels. Higher levels of *M*, such as 0.455, results in a large proportion of mortality in the population being attributed to natural causes such as changes in the environment or predation. This is unlikely given the high fishing pressure exerted on this reef species in Greater Darwin Region and the fact that higher values of *M* are inconsistent with the life history of this species (Section 3.5.5).

Steepness (*h*)

Four different scenarios are used to explore the sensitivity of the assumed steepness (*h*) value in the population model. No substantial difference is observed in the biomass depletion trajectories, with 2021 depletion having similar median values and confidence bounds across all values of *h* from 0.5 to 0.8 (Figure 15). Estimating *h* within the model requires good contrast in the data at low and high population sizes (Tagliarolo et al., 2021), which is not the case for this fish stock. The likelihood profile shows that the available data had little information on *h* as the change in negative log likelihood progresses non-linearly (Figure C 6).

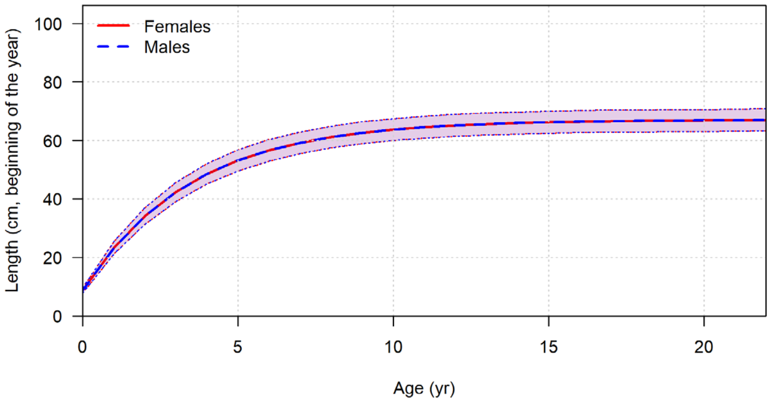
Asymptotic Length

There is substantial difference in the final biomass depletion in 2021 when the average asymptotic length in the model was pre-specified with a value of 76 rather than 67. The larger average asymptotic length results in a relative biomass that is 14% of unfished levels (50^{th} percentile) with values ranging from 9% to 20% of unfished levels (Figure 16a). Given the absence of conditional age-at-length data for this stock, there is insufficient information to estimate the parameter within the model. The likelihood profile shows there is apparent data conflict across all data sources used in the assessment (Figure C 7).

CPUE standardisation

There is substantial difference in the final biomass depletion in 2021 when the CPUE is standardised using the ‘spatial averaging’ technique. The relative biomass appears to be more depleted when compared to the reference model (where CPUE is standardised using a GLM). The estimated biomass is 4.6% of unfished levels (50^{th} percentile) with values ranging from 3.1% to 6% of unfished levels (Figure 16b). This shows that the assumptions used in the ‘spatial averaging’ technique, such as back-casting CPUE values for empty grids have significant influence on the model outcome in Stock Synthesis. However, the spatial averaging technique fails to account for a number of factors that impact the catch rate (e.g. fisher skill, seasonal effects, etc.).

(a)



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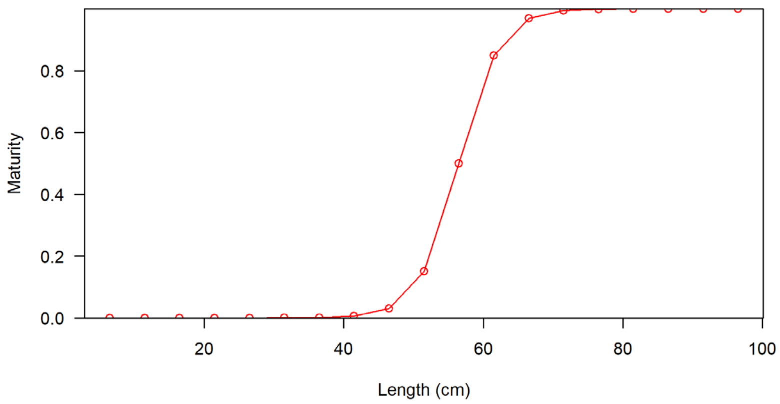

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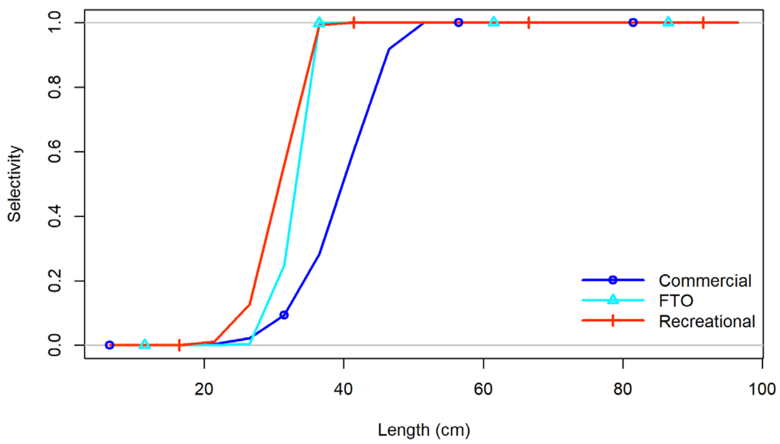
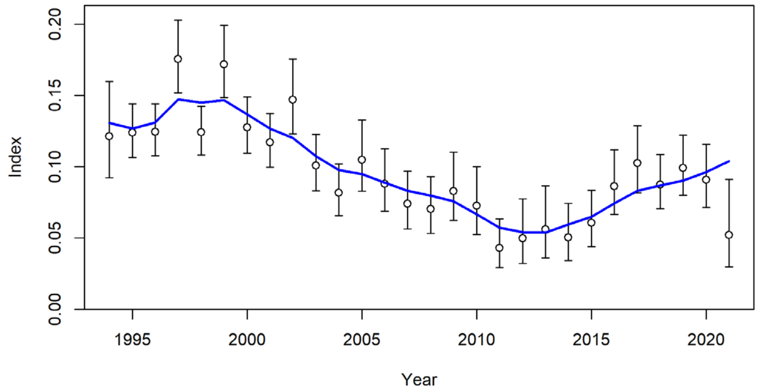


Figure 12: Portfolio of life history and parameters used for stock assessment (a) growth of fish showing length vs age with 95% confidence intervals; (b) maturity vs length showing the fraction of population that are mature (for both males and females); (c) selectivity parameters estimated within the model for FTO and recreational sector using length composition data.

(a)



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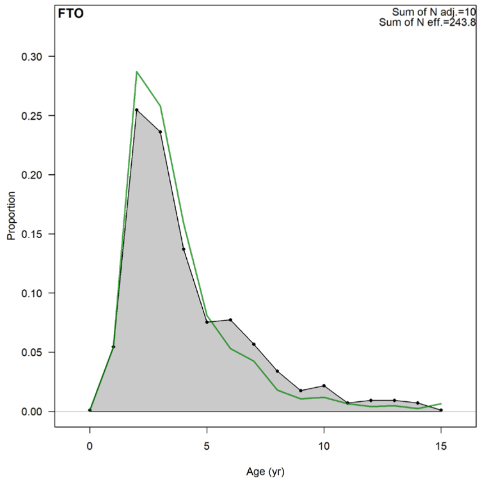

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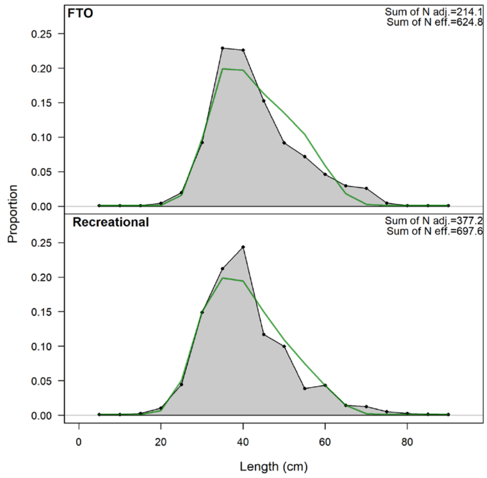
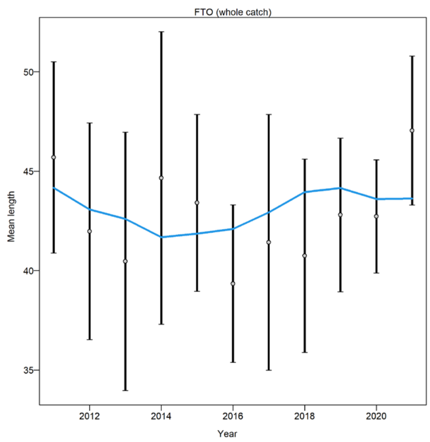


(d)



(e)

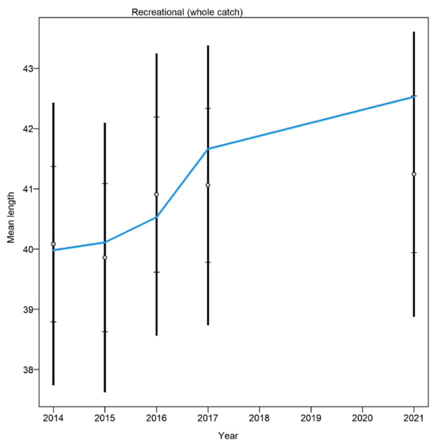
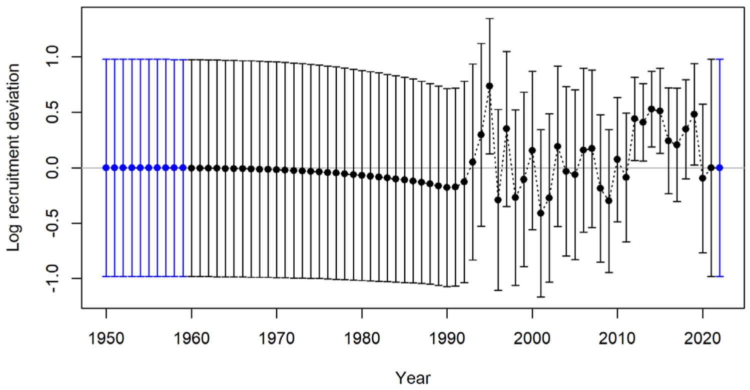
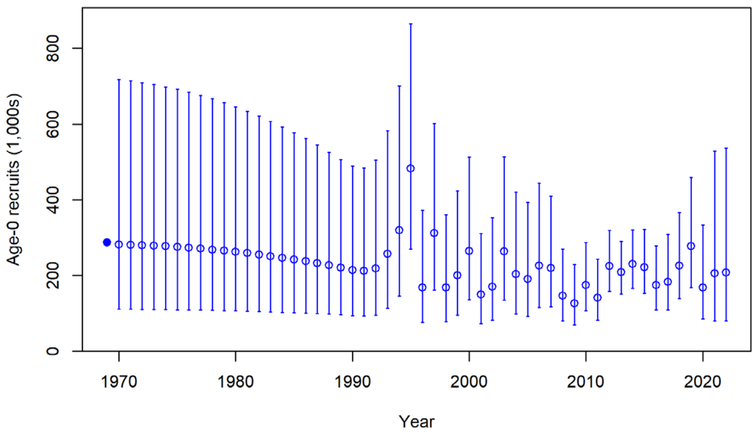


Figure 13: Model fit to data used for stock assessment (a) fits to the annual FTO CPUE; (b) fits to the age composition data from the FTO sector aggregated across all years; (c) fits to the aggregated length composition data from FTO and recreational sector aggregated across all years; (d) data weighting of mean length data for the FTO sector by year, with 95% confidence intervals based on current sample size (Francis method value: 1) and (e) data weighting of mean length data for the recreational sector by year, with 95% confidence intervals based on current sample size (Francis method value: 3.3064).

(a)



(b)



(c)

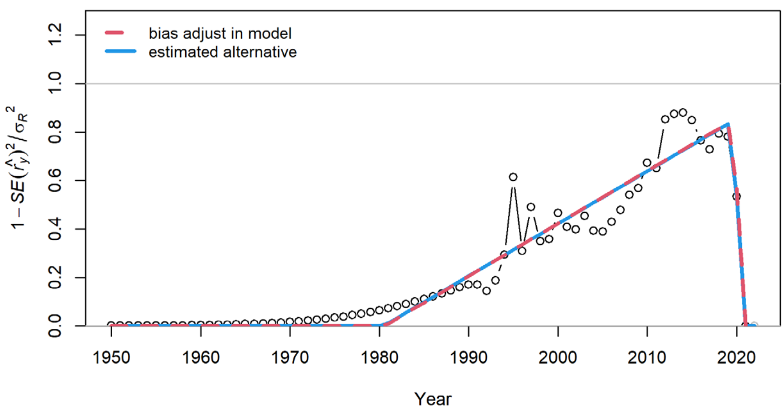


Figure 14: Stock recruitment in the reference model (a) the estimated times of recruitment deviations used in the model starting from year 1950 onwards with ~95% asymptotic intervals (b) the estimated time series of recruitment at age 0 estimated by the model from 1970 to 2021 with ~95% asymptotic intervals (c) recruitment deviation bias ramp adjustment applied to the model to ensure estimated recruitment events are mean unbiased.

(a)

(b)

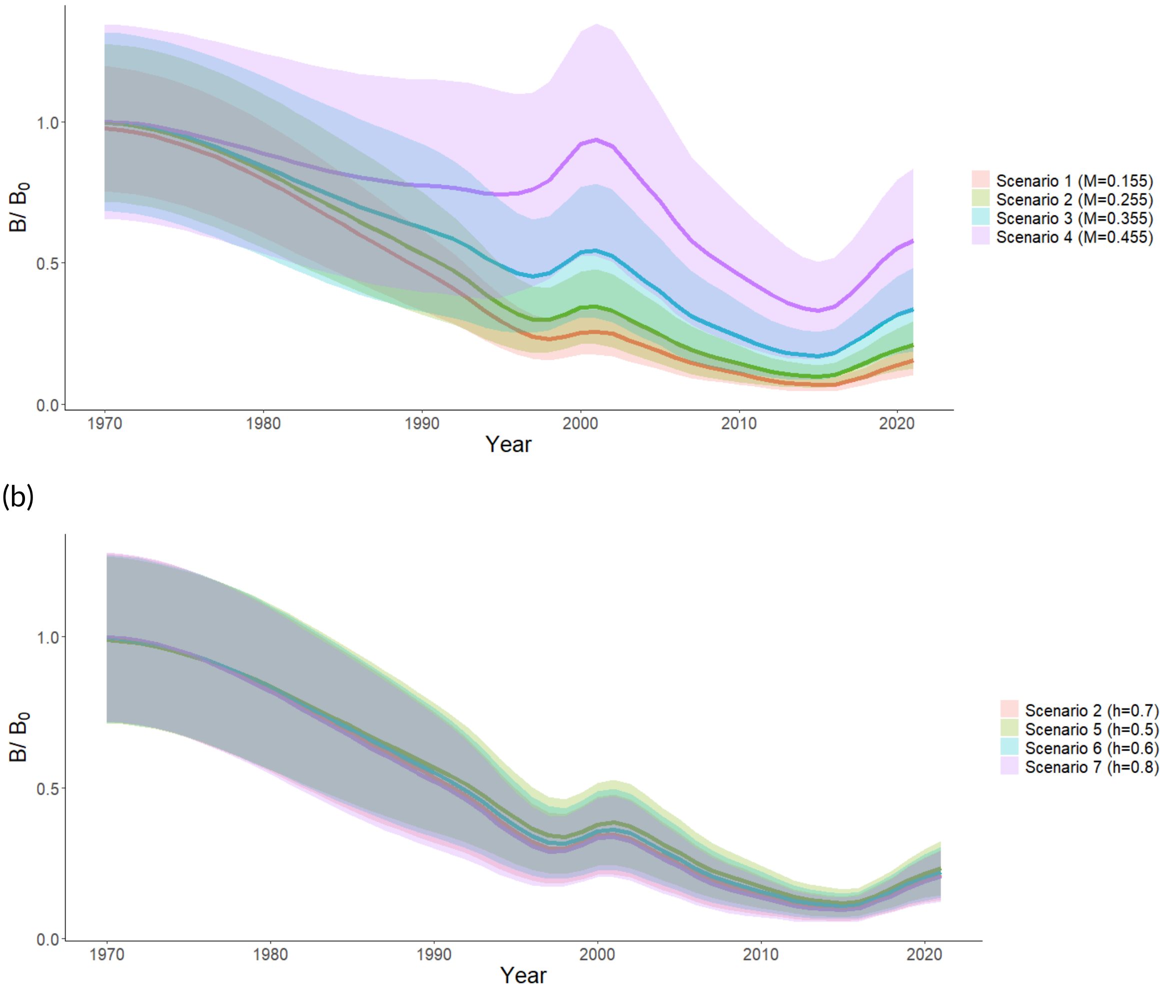


Figure 15: Sensitivity analysis of reference model on (a) the assumption of natural mortality *M* and (b) the assumption of steepness *h*, with ~95% asymptotic intervals

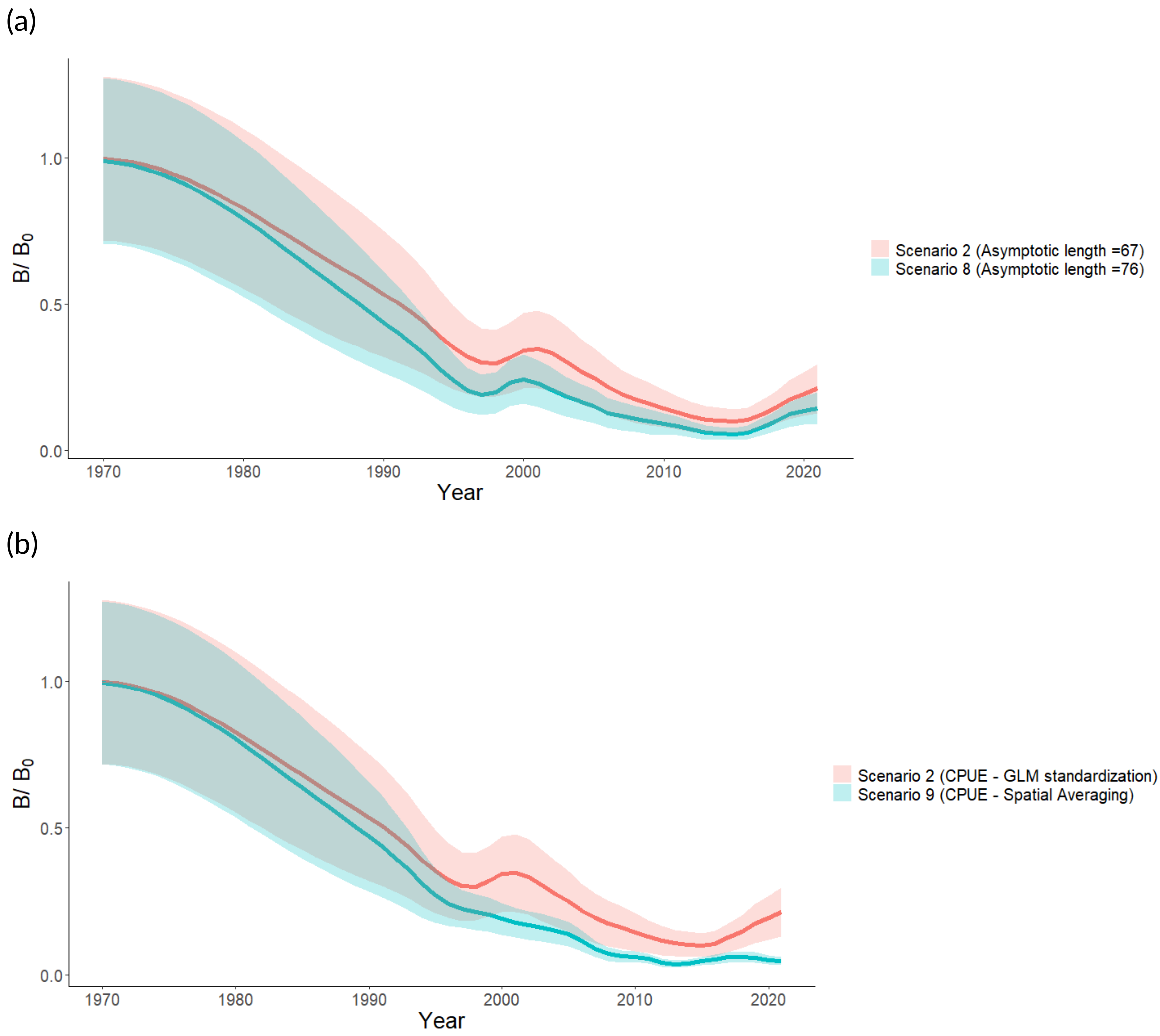


Figure 16: Sensitivity analysis of reference model on (a) the assumption of asymptotic length L_∞ and (b) the technique used for CPUE standardisation, with ~95% asymptotic intervals.

3.6. Stock status: Greater Darwin Region

Based on the evidence provided, the status of Golden Snapper in the Greater Darwin Region has been classified as **Depleting**. Biomass in 2021 (B_{2021}) was estimated to be between 13%-29% (5th and 95th percentile) with a median at 21% of unfished levels. Fishing mortality in 2021 (F_{2021}) is above F_{MSY}, the level of fishing that is considered sustainable in the long term. Hence, it is highly likely that stocks of Golden Snapper in the Greater Darwin Region are close to being **recruitment overfished** (21% B/B_0) and that **recruitment overfishing** is occurring.

3.7. Bridging Analysis

Previous stock assessments of Golden Snapper in the NT have been undertaken using a stochastic SRA. Aside from the change in modelling approach, there are two main differences between this assessment and the previous undertaken in 2017. First, a GLM approach to standardising FTO CPUE has been introduced, which is discussed in detail in Section 3.2.2. The second relates to the reconstruction of recreational catch estimates, the sector which contributes the greatest catch for this assessment unit. Since the last assessment was undertaken the results from several recreational fishing surveys have become available, which provide additional estimates of catch and fishing participation rates. Further, length data obtained from ongoing FTO monitoring has provided updated estimates of fish size that have been used to convert the number fish caught to the weights used in this assessment. A number of stochastic SRA models have been developed (Table 8) to explore the differences in outcome as a consequence of:

1. Moving from a stochastic SRA to Stock Synthesis as the preferred stock assessment approach.
2. Moving from 'Spatial Averaging' to 'Generalised Linear Modelling' as the preferred standardisation method for the abundance index.
3. Updated estimates of recreational catch and participation from recent recreational fishing surveys.

Length data could not be confidently incorporated into the stochastic SRA model and was not explored in this bridging analysis.

Table 8: Scenarios explored for the bridging analysis in Stock Reduction Analysis

Scenario	Abundance Index	Catch history	Last year of assessment
Scenario 10	Spatially averaged catch rate	2017 method	2017
Scenario 11	Spatially averaged catch rate	2021 method	2017
Scenario 12	GLM standardised catch rate	2021 method	2017
Scenario 13	GLM standardised catch rate	2021 method	2021
Scenario 14	Spatially averaged catch rate	2021 method	2021

Table 9: Life history and biological parameters provided in SRA for the assessment of Golden Snapper in the Greater Darwin Region.

Acronym	Description	Parameter	Estimated or Pre-specified
K	Von Bertalanffy Growth Parameter	0.28	Pre-specified, no prior
L_{inf}	Asymptotic length	67 cm	Pre-specified, no prior
L_{mat}	Length at 50% maturity	38 cm	Pre-specified, no prior
A_{mat}	Age at 50% maturity	4	Pre-specified, no prior
S	Survival (1- Natural Mortality)	40% to 80%	Pre-specified, no prior
CV_{age}	Coefficient of variation in length at age	0.09	Pre-specified, no prior
Wt_{100}	Weight at length of 100 cm	11 kg	Pre-specified, no prior
t_0	Length at age 0	0 cm	Pre-specified, no prior
SD_{rec}	Standard deviation in recruitment	0.2	Pre-specified, no prior
ρ	Autocorrelation in recruitment	0	Pre-specified, no prior

Table 10: Input data for SRA for the assessment of Golden Snapper in the Greater Darwin Region.

Data Type	Description
Catch Time Series	Total removals from all sectors and discards in each year
Abundance Index	GLM standardised catch rate/Spatially averaged catch rate
Age composition	Age composition data from 2010
Vulnerability/Selectivity	100% of population vulnerable to fishing from age 1 onwards

3.7.1. SRA outcomes[2]

The impacts of the new catch history and CPUE standardisation approach were examined by introducing these new data streams into the 2017 assessment in successive scenarios (Table 8). The 2017 stochastic SRA for Golden Snapper indicated that stocks in the Greater Darwin Region were recruitment overfished (99% probability) and existing fishing pressure would likely cause recruitment overfishing in the future (80% probability; Figure 17).

The introduction of the new catch reconstruction resulted in more pessimistic estimates of both the egg production and fishing mortality in 2021 (Figure 17). The application of a GLM standardised CPUE, in addition to the new recreational catch reconstruction, resulted in a model that had a very similar outcome to the original 2017 assessment (Figure 17).

The stochastic SRA's with data to 2021 resulted in final year outcomes that were similar to those with data to 2017 (Figure 18), although in this instance, it was the spatially averaged CPUE that produced the more pessimistic estimate of status.

While it is difficult to make direct comparisons between stock synthesis and the stochastic SRA models, overall the SRA assessments produced a more pessimistic outcome of stock status than the SS reference model. Varying the data inputs at times changed the outcomes of the SRA models, although none of these variations resulted in a change of status. All SRA scenarios explored indicate that Golden Snapper in the Great Darwin Region are depleted.

[2] The stock status is determined using the phase plot provided in the SRA package by Lombardi and Walters (2011), which is consistent with those presented in the 2017 stock assessment report (Saunders, 2018). The phase plot indicate Spawning Stock Biomass (*SSB)* in the final year (*E*) relative to unfished *SSB* (E_0) against the exploitation (*U*) relative to its *MSY* equivalent (U_{MSY}).

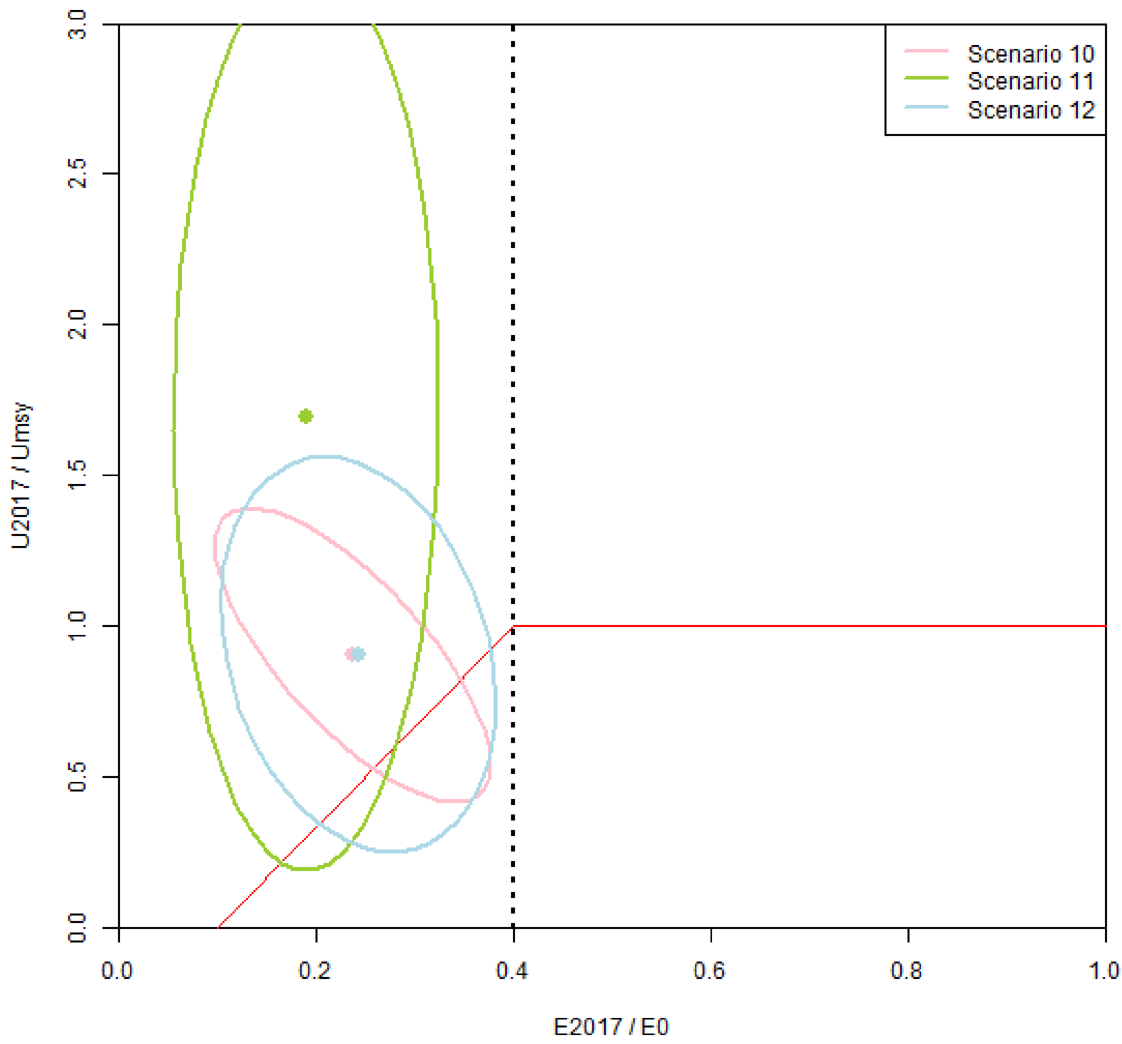


Figure 17: Stock status output from the stochastic SRA assessment scenarios exploring the implications of different catch time series and CPUE standardisation techniques with data to 2017. Scenario 10 is modelling outcomes of the 2017 assessment. Scenario 11 is the outcome of the 2017 assessment using the newly derived catch history. Scenario 12 is the outcome of the assessment that applies the new catch history and the GLM standardised CPUE.

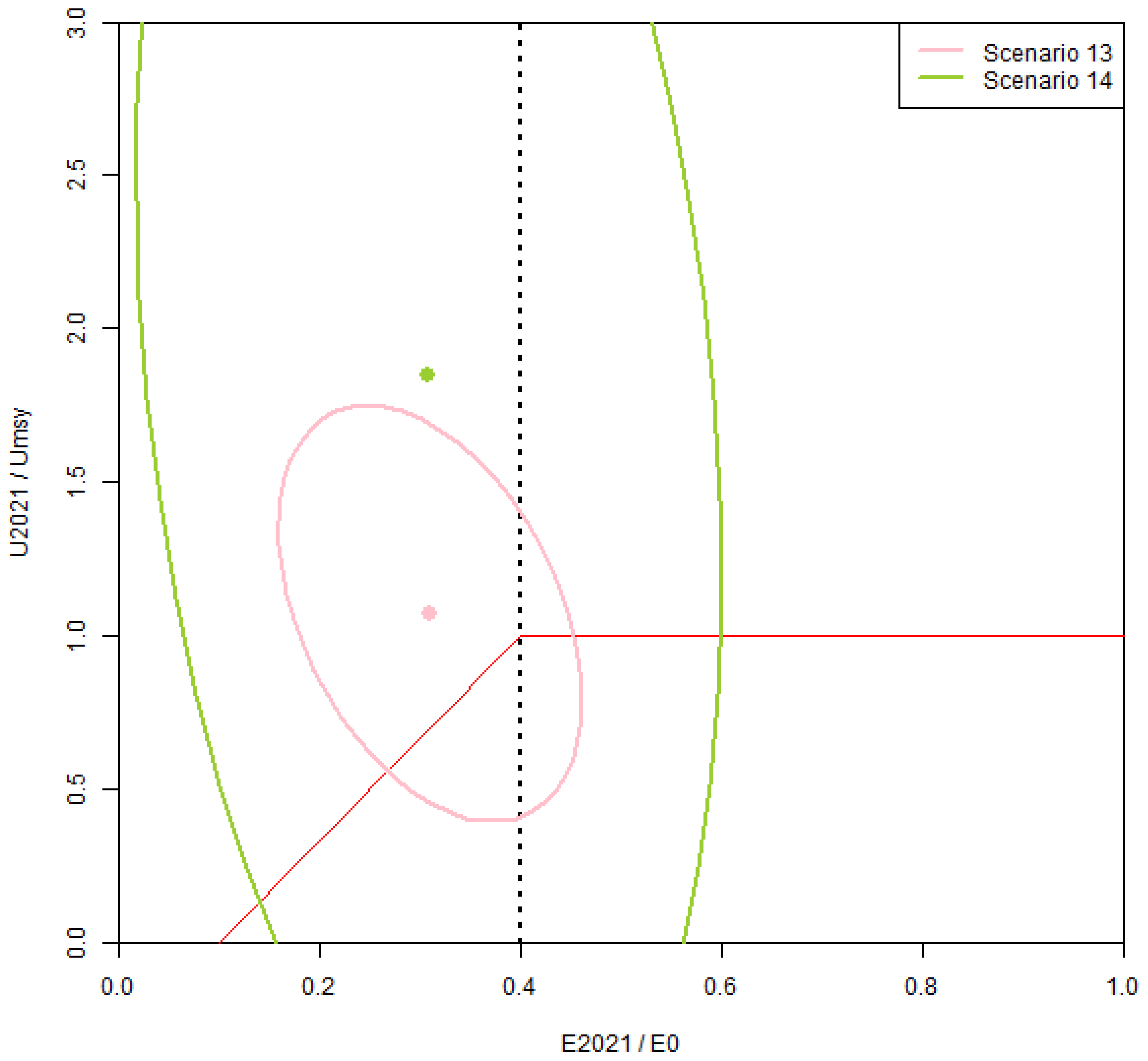


Figure 18: Stock status output from the stochastic SRA assessment scenarios exploring the implications of different catch time series and CPUE standardisation techniques with data to 2021. Scenario 13 is modelling outcomes of the SRA including data used in the reference model in this assessment, excluding the length data. Scenario 14 are the outcomes of the SRA with spatially averaged CPUE data to 2021.

4. Regional Northern Territory Assessment

The Regional Northern Territory assessment unit encompasses all the coastal and nearshore waters of Northern Arafura Sea and the entire Timor Sea within the NT Fishing zone but excluding the spatial grids associated to the Greater Darwin Region (Figure 19). The majority of fishing activity in this assessment unit is by the demersal trawlers and to a much lesser extent by mobile fish traps. This assessment unit encompasses multiple biological stocks, however, as these populations likely receive similar fishing pressure, they have been grouped to a single assessment unit.

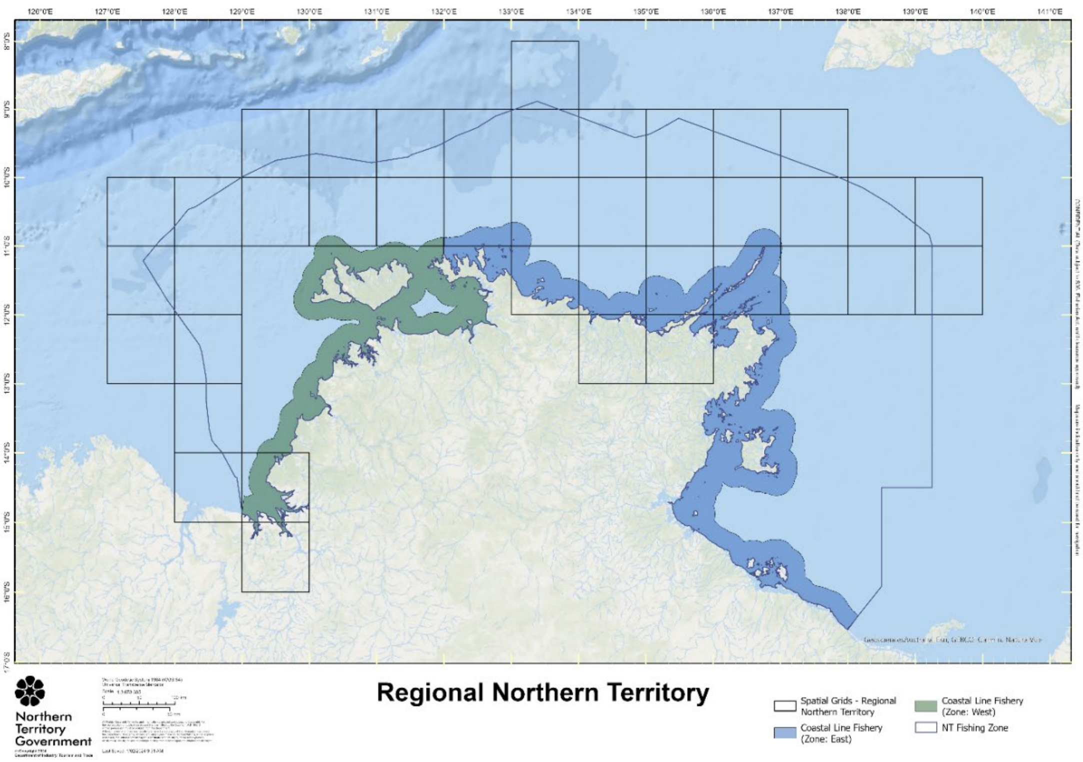


Figure 19: Regional Northern Territory assessment area, spatial grids represent the area from which the commercial catch and effort data were derived. The dark green and dark blue shaded region represents the boundaries of the Western Zone and Eastern Zone of Coastal Line Fishery (CLF) although much of the Golden Snapper removals are by the trawlers in Demersal Fishery that operate beyond the CLF boundary in the NT Fishing Zone.

4.1. Catch history

4.1.1. Foreign fishing

The Arafura and Timor Seas, to the north of Australia, have been fished at varying intensities for more than 50 years. Commercial operations began with Japanese stern trawlers operating from the late 1950s to the early 1960s, when these were international waters. During the 1970s, Taiwanese pair trawlers fished northern Australian waters intensively and, after the ratification of the Australian Fishing Zone in 1979, Thai and Chinese vessels joined the existing fleet and continued to fish under Australian licence agreements until 1990.

Due to increasing interest by domestic operators and concerns about overfishing of snapper resources in the region, access by foreign fleets ceased in 1991. The highest annual catch of Golden Snapper taken from this resource is estimated at around 140 tonnes in 1989 (Figure 20).

4.1.2. Domestic fishing

Commercial sector

Following the cessation of foreign fishing, fishing for offshore snapper using lines and fish traps was managed through the establishment of the TRF and DF. Trawling was permitted under the Commonwealth Northern Trawl Fishery which later became the NT Finfish Trawl Fishery. In 1995, management responsibility of the offshore snapper fisheries in waters adjacent to the NT passed to the NT Fisheries Joint Authority. By then, there was only one trawl operator working in NT waters. Until 1999, most fishing occurred either in the TRF (targeting Goldband Snapper) or the Finfish Trawl Fishery (targeting Red Snappers). In February 2012, the Finfish Trawl Fishery was incorporated into the Demersal Fishery. Currently, 97% of the commercial Golden Snapper harvest is by the Demersal Fishery and Timor Reef Fishery combined averaging 30 tonnes in the last 10 years.

Average Golden Snapper catch by the Coastal Line Fishery from the Regional Northern Territory assessment area is under 2 tonnes/annum for the last decade. Incidental catches are reported by the Offshore Net and Line Fishery that predominantly use ‘pelagic nets’ to target Grey mackerels and sharks in this region. Additionally, some catch are reported under the Aboriginal Coastal Licence, however, this is mostly under 0.1 tonnes per annum.

Harvest by other sectors

Fishing Tour Operator harvest has been stable in the past decade with annual catches averaging around 15 tonnes. Harvest by the recreational sector is estimated at an average of 13 tonnes based on catch reconstructed from NT wide recreational survey reports (Coleman, 2003, 1998; West et al., 2022, 2012).

Recreational catch reconstruction

Estimates of recreational catch of Golden Snapper (North and West coast) are available for certain years from reports of NT wide recreational surveys conducted in 2000, 2009-10 and 2018-19 (Coleman, 1998; West et al., 2022, 2012). Based on these reports, annual catch was reconstructed by multiplying per capita fish caught with the number of fishers. Number of fishers in each year is estimated by multiplying the NT population with participation rates. The participation rates and per capita fish caught were sourced from NT wide recreational survey reports but a linear interpolation was applied for missing years.

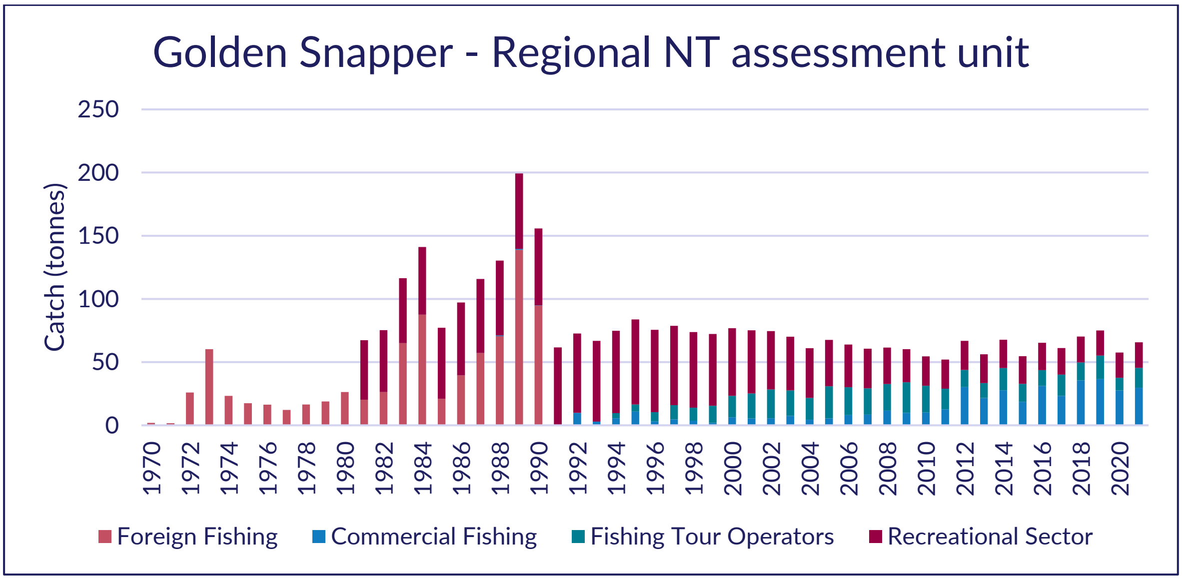


Figure 20: Total annual Golden Snapper catch from the Regional Northern Territory assessment unit by all fishing sectors (i.e., commercial, Fishing Tour Operators and recreational sectors) from 1970 – 2021.

4.2. Fishery Independent Survey

A fishery independent trawl survey was conducted between July to October in 2021 to estimate the biomass of tropical snappers across Northern Australia (Knuckey and Koopman, 2022). As additional surveys are conducted in the future, the biomass estimates are expected to evolve into a time series that can be effectively employed in stock assessments. However, the 2021 survey does provide an estimate of abundance for Golden Snapper that can be used with some caution (Knuckey and Koopman, 2022).

The survey estimated biomass of Golden Snapper in nine strata across NT waters (Figure 21). The strata were defined from a combination of fishing catch and effort, divisions of geographic divisions' basins and sub-basins and fishery boundaries. The estimated biomass of Golden Snapper from all strata encompassing the 'Regional NT Assessment' unit is 3276 tonnes with a CV of 0.37 (i.e., excluding GoC North Primary and GoC Southwest Secondary strata). The estimated catch of Golden Snapper in 2021 is 62.5 tonnes, representing a harvest fraction of 1.9% of the estimated biomass with a confidence interval from 1.1% to 6.9% of the estimated biomass.

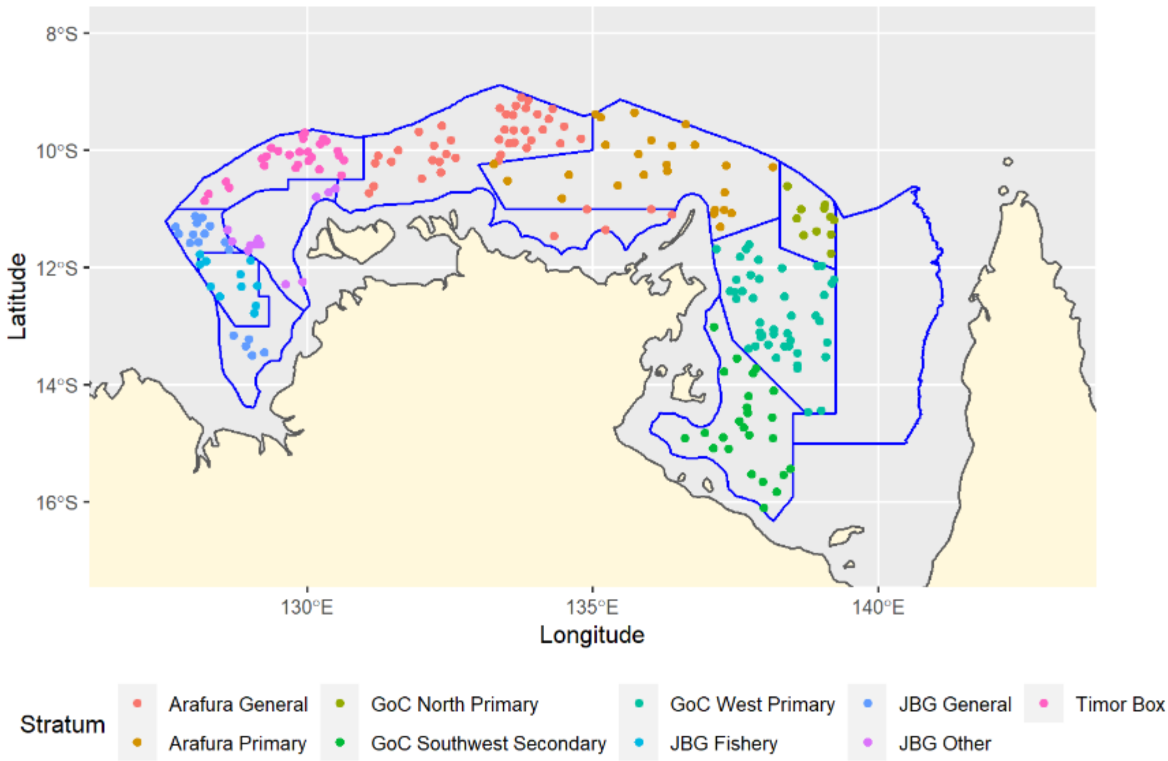


Figure 21: Strata used for the trawl based fishery independent survey in 2021 (Knuckey and Koopman, 2022). Dots in the map indicate the trawl sites. The stratum with no dots towards right of the Gulf of Carpentaria is the Queensland component that is not considered for the assessment in this report.

4.3. Catch-MSY

The Regional Northern Territory assessment unit was assessed using a Catch-MSY model in the 'datalowSA' R package (Haddon, 2020). A detailed description of the model is provided in Section 2.6. Significant changes in comparison to the previous assessment undertaken in 2020 are:

1) The process of historical catch re-construction of the recreational component (described in Section 3.1.1.)
2) The upper limit on the assumption of resilience 'r' has been updated from 0.5 to 0.7 in the current assessment to ensure all possible r-K pairs are explored by the model.

4.3.1. Input data and parameters

The Catch-MSY model only requires a time series of the catch data from the stock to indicate the total harvest levels. Other inputs into the Catch-MSY model (Table 11) indicate the assumptions and priors required for running the model.

Note, there is greater uncertainty with the outcomes from Catch-MSY as a consequence of using limited data as input to the model.

Table 11: Input parameters for Catch-MSY model undertaken in the Regional NT assessment unit.

Parameter	Regional NT
Catch time series	1970 - 2021
Starting population growth rates	0.05 to 0.7
Lower limit for starting K values	Maximum catch in the time series
Upper limit for starting K values	100 X Maximum catch in the time series
Multiplier for carrying capacity (K)	Set equal to 1
Priors for initial depletion	70% - 99% of unfished levels
Priors for final depletion	5% - 99% of unfished levels
Process error	0.025 (adopted from 2020 assessment)
Constrain applied on harvest rate (H)	No constraints
Number of iterations	20,000

4.4. Stock assessment outcome

Stock assessment using the Catch-MSY method shows that the median estimated biomass in 2021 is at 84% of unfished levels with a confidence interval from 39% to 95% of unfished levels. The depletion trajectory in Figure 22a shows that the stock biomass was relatively stable at ~90% of unfished levels in early years. The increase in catch by foreign fleets from 1980's until 1990's reduced the biomass to 67% of unfished levels but then reverted back to around 84% when this fishing ceased. The biomass remained stable between 78% and 85% of unfished levels for the last 20 years. The trend in fishing mortality also indicates no significant change in fishing pressure on the stock since the early 2000's (Figure 22b). The outcome from 20,000 iterations of Catch-MSY shows that by the end of 2021, the stock is in a 'sustainable' position with 98% probability (Figure 22, Table 12). This outcome is further supported by the low harvest fraction when compared to the estimated biomass from the 2021 fishery independent survey.

There is high uncertainty in the estimates of biomass depletion and fishing mortality derived from catch data using Schaefer production model-assisted Catch-MSY analysis. In particular, Catch-MSY is poor at providing precise estimates of depletion, but its negative biomasses are most likely to be over-precautionary outputs, especially in lightly fished stocks (Free et al., 2020). The evidence for the imprecise estimates of depletion are obvious with the wide confidence intervals produced by the model.

There is increasing evidence that catch-only methods produce imprecise and biased estimates of biomass depletion and catch data alone generally perform poor in classifying stock status (Dai et al., 2023; Free et al., 2020). The current assessment is considered in that context and the final determination of stock status is not solely reliant on this Catch-MSY assessment.

Table 12: Decision table to determine the stock status in Regional Northern Territory assessment unit. The table provide the distribution of stock status outcome from 20,000 iterations of Catch-MSY model.

Stock status	Below $B_{20\%}$	Above $B_{20\%}$
Above F_{MSY}	Depleted 1.04%	Depleting 0.19%
Below F_{MSY}	Recovering 0.24%	Sustainable 98.25%

4.5. Stock status: Regional Northern Territory

Based on the evidence provided, the status of stock has been classified as **Sustainable**.

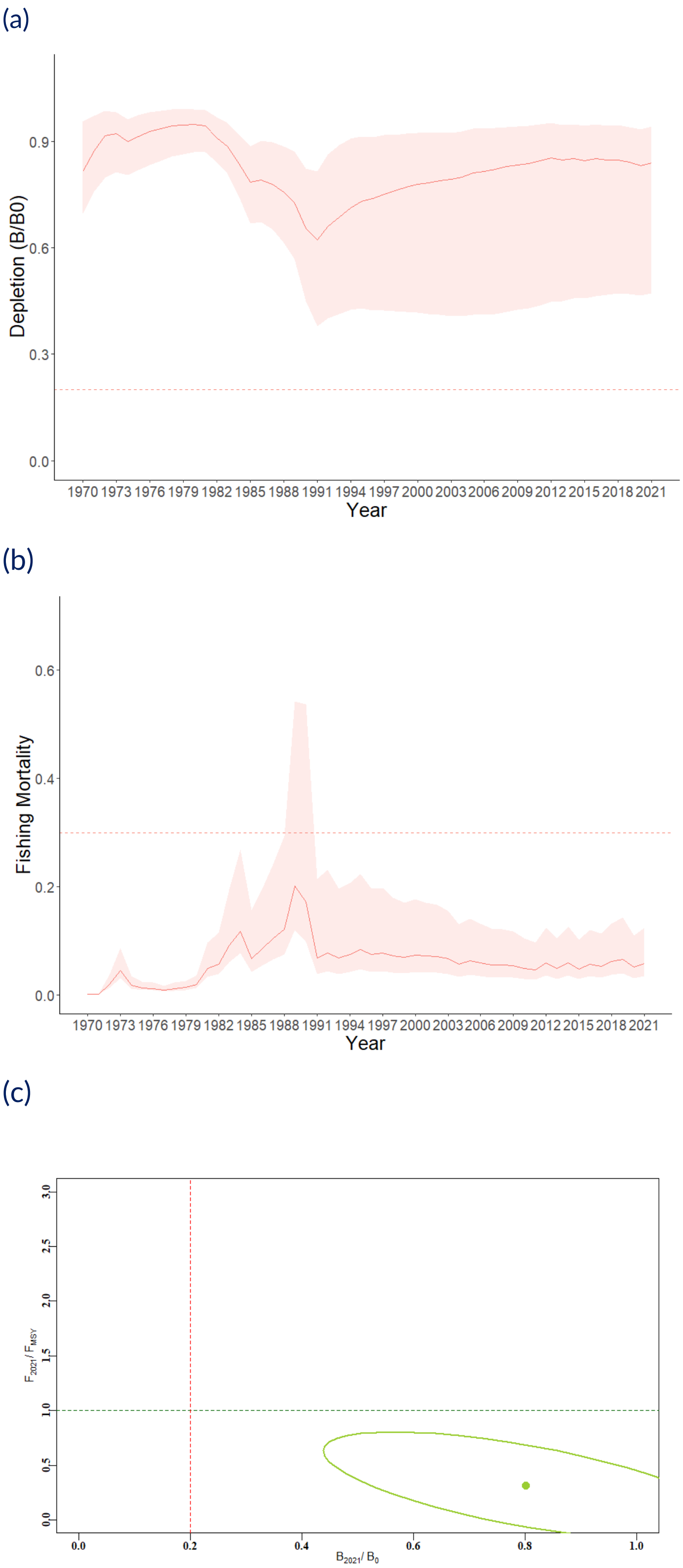


Figure 22: Catch-MSY outcome for Golden Snapper assessment in the Regional Northern Territory assessment unit (a) depletion of stock biomass since 1970 assuming 70-99% initial depletion, dotted line indicates 20% unfished level with ~95% asymptotic intervals (b) trend of fishing mortality between 1970 and 2021, dotted line indicates the F_{MSY} with ~asymptotic intervals (b) phase plot indicating the status of fish stock in 2021 relative to the reference points. The circle indicate the 95th percentile boundary of stock position from 20,000 model runs (see Figure 3).

5. Gulf of Carpentaria Assessment

The Gulf of Carpentaria (GOC) assessment unit encompasses all the coastal, nearshore and offshore waters of Western Gulf of Carpentaria Sea that are within the NT Fishing zone (Figure 23). The majority of fishing activity in this assessment unit is by the demersal trawlers and to a much lesser extent by mobile fish traps. Recreational and Fishing Tour Operators (FTO) fishing effort in this assessment unit occurs mostly around Nhulunbuy, Groote Eylandt and the McArthur region. This assessment unit likely encompasses multiple biological stocks that are assessed as a single unit.

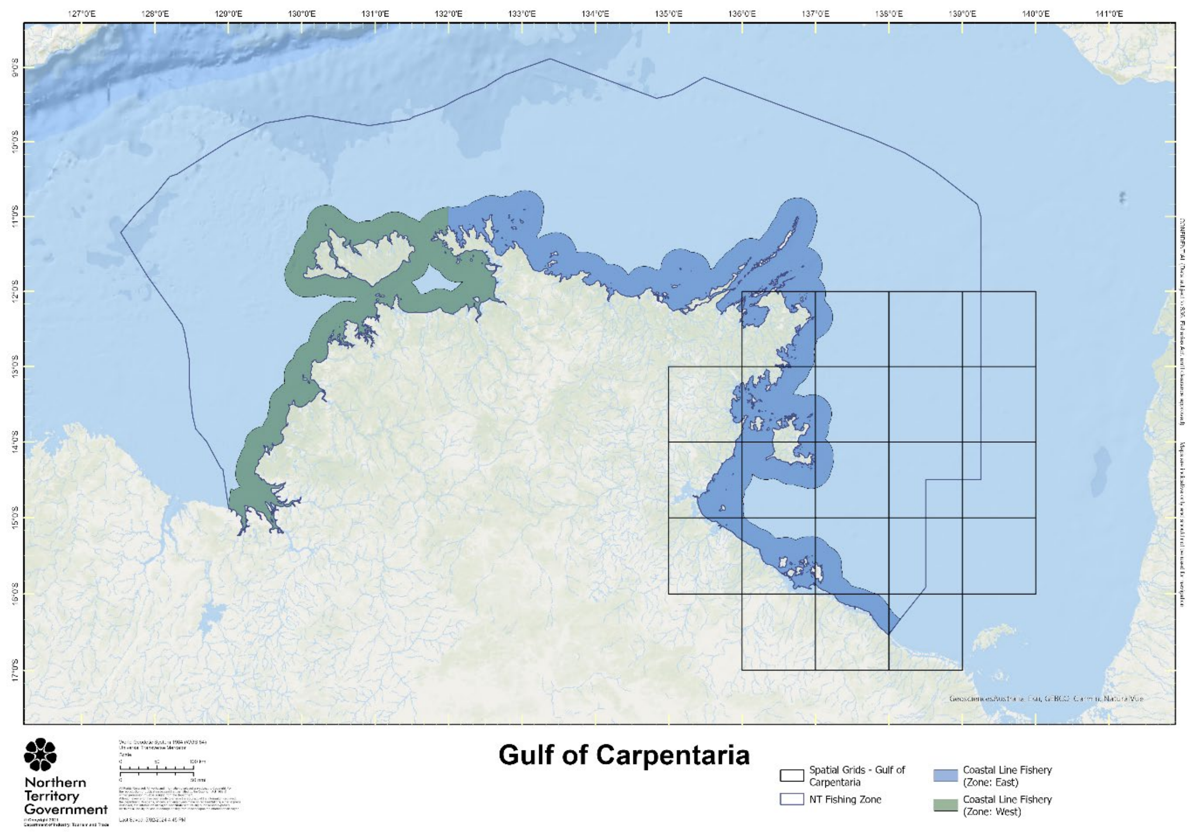


Figure 23: Gulf of Carpentaria (GOC) assessment area, spatial grids represent the area from which catch and effort data were derived. The dark green and dark blue shaded region represents the boundaries of the Western Zone and Eastern Zone of Coastal Line Fishery (CLF), although much of the Golden Snapper removals are by trawlers in Demersal Fishery that operate beyond the CLF boundary.

5.1. Catch history

5.1.1. Foreign fishing

The GOC region has been fished at varying intensities for more than 50 years. Commercial operations began with Japanese stern trawlers operating from the late 1950s to the early 1960s when these were international waters. There is anecdotal evidence that the annual catch of Golden Snapper during the 1950s was under 1 tonne. During the 1970s, Taiwanese pair trawlers fished northern Australian waters intensively and, after the ratification of the Australian Fishing Zone in 1979, Thai and Chinese vessels joined the existing fleet and continued to fish under Australian licence agreements until 1990. Due to increasing interest by domestic operators and concerns about overfishing of snapper resources in the region, access by foreign fleets ceased in 1991.

There is low confidence in the historical data prior to the 1980s and hence it was not considered for Catch-MSY assessment. However, we assume the stocks were at most 50% depleted at the start year used for the assessment (1981).

5.1.2. Domestic fishing

Commercial sector

Until 1999, most fishing occurred in the Finfish Trawl Fishery (targeting Red Snappers). In February 2012, the Finfish Trawl Fishery was incorporated into the Demersal Fishery. In the last decade, 85% to 100% of the Golden Snapper commercial harvest in the GOC region was by the Demersal Fishery averaging 1.5 tonnes, except for 2019 in which the catch was at 19 tonnes (Figure 24).

Average Golden Snapper catch by the Coastal Line Fishery from the GOC assessment unit is under 1 tonne/annum for the last decade. Incidental catches are reported by the Offshore Net and Line Fishery that predominantly uses 'pelagic nets' to target Grey Mackerel and sharks.

Harvest by other sectors

Harvest by Fishing Tour Operators increased from 0.02 tonne in 2012 to around 1 tonne in 2021. Harvest by the recreational sector is relatively stable in the last decade which is estimated at an average of 3 tonnes/year based on catch reconstructed from NT wide recreational survey reports (Coleman, 2003, 1998; West et al., 2022, 2012). The recreational catch was reconstructed in a similar way as detailed in the 'Regional NT assessment' unit (Section 2.5.1), but using the data from 'East Coast/Gulf area'.

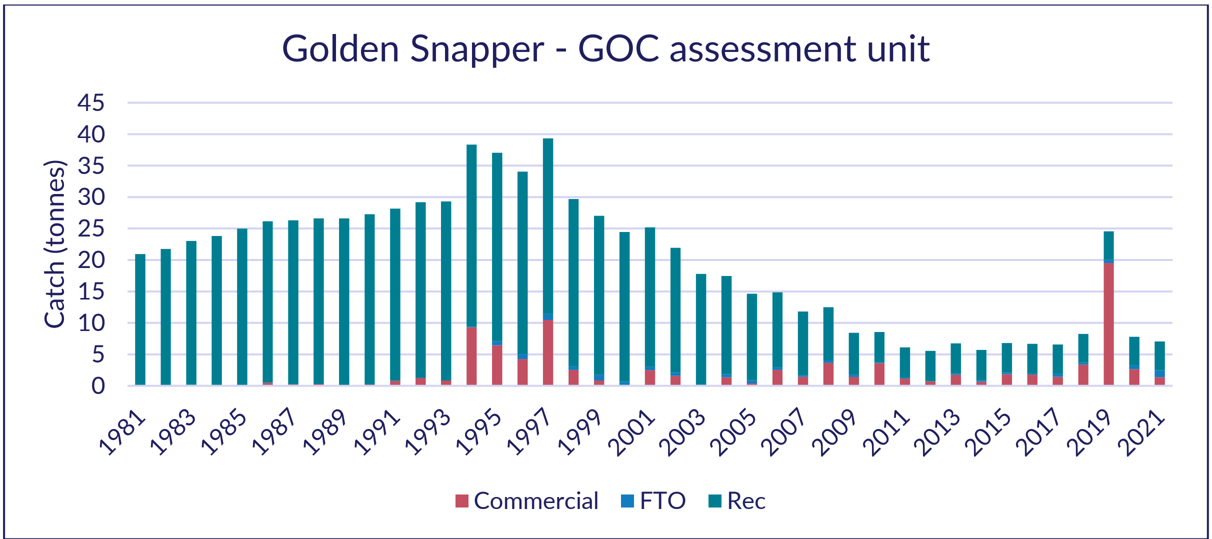


Figure 24: Total annual Golden Snapper catch from the GOC assessment unit by all fishing sectors (commercial, Fishing Tour Operators and recreational sectors) from 1981 - 2021.

5.2. Fishery Independent Survey

A fishery independent trawl survey was conducted between July to October in 2021 to estimate the biomass of tropical snappers across Northern Australia (Knuckey and Koopman, 2022). More details about this survey are provided in Section 4.2. The estimated biomass of Golden Snapper from all strata encompassing the 'Gulf of Carpentaria Assessment' unit is 1061 tonnes with a CV of 0.37 (i.e., GoC North Primary and GoC Southwest Secondary strata). The estimated catch of Golden Snapper in 2021 is 6.32 tonnes, representing a harvest fraction of 0.59% with a confidence interval from 0.34% to 2.1% of the estimated biomass.

5.3. Catch-MSY

The GOC stock in the present report was assessed using the Catch-MSY model which is essentially the same model used in the previous assessment but with updated annual catch data and model parameters. Catch-MSY was initially described by Martell and Froese (2013) and later modified by Haddon (2020) and is available in the 'datalowSA' R package (Haddon, 2020). A detailed description of the model is provided in Section 2.6. Significant changes in comparison to the previous assessment undertaken in 2020 are:

1) The process of historical catch re-construction of the recreational component (described in Section 3.1.1.)
2) The upper limit on the assumption of resilience 'r' has been updated from 0.4 to 0.7 in the current assessment to ensure all possible r-K pairs are explored by the model.

5.3.1. Input data and parameters

The inputs for the Catch-MSY model that indicate the assumptions and priors are outlined in Table 13.

Table 13: Input parameters for Catch-MSY model undertaken in the Gulf of Carpentaria assessment unit.

Parameter	Gulf of Carpentaria NT
Catch time series	1981 - 2021
Starting population growth rates	0.05 to 0.7
Lower limit for starting K values	Maximum catch in the time series
Upper limit for starting K values	100 X Maximum catch in the time series
Multiplier for carrying capacity (K)	Set equal to 1
Priors for initial depletion	50% - 99% of unfished levels
Priors for final depletion	5% - 99% of unfished levels
Process error	0.025 (adopted from 2020 assessment)
Constrain applied on harvest rate (H)	No constraints
Number of iterations	20,000

5.4. Stock assessment outcome

Stock assessment using the Catch-MSY method shows that the median estimated biomass in 2021 is at 90% of unfished levels with a confidence interval from 60% to 97% of unfished levels. The depletion trajectory in Figure 25a shows that the stock biomass was relatively stable at around ~75% of unfished levels between 1981 and 1992. The increase in estimated catch between 1993 and 1998 is primarily from the commercial sector. The trend in fishing mortality indicates a significant reduction in fishing pressure since the late 1990s, which has resulted in an increase in biomass to 93% of unfished levels by 2018 (Figure 25b). The Demersal Fishery recorded a peak harvest of 19 tonnes of Golden Snapper in 2019 that reduced the biomass to 90% unfished levels in 2021. The outcome from 20,000 iterations of Catch-MSY shows that by the end of 2021, the stock is in a 'sustainable' position with 99% probability (Figure 25c, Table 14). This outcome is further supported by the low harvest fraction when compared to the estimate biomass from the 2021 fishery independent survey.

There is high uncertainty in the estimates of biomass depletion and fishing mortality derived from catch data using Schaefer production model-assisted Catch-MSY analysis. In particular, Catch MSY is poor at providing precise estimates of depletion, but its negative biomasses are most likely to be over-precautionary outputs, especially in lightly fished stocks (Free et al., 2020). The evidence for the imprecise estimates of depletion are obvious with the wide confidence intervals produced by the model.

There is increasing evidence that catch-only methods produce imprecise and biased estimates of biomass depletion and catch data alone generally perform poor in classifying stock status (Dai et al., 2023; Free et al., 2020). The current assessment is considered in that context and the final determination of stock status is not solely reliant on this Catch-MSY assessment.

Table 14: Decision table to determine the stock status in the Gulf of Carpentaria. The table provide the distribution of stock status outcome from 20,000 iterations of Catch-MSY model.

Stock status	Below $B_{20\%}$	Above $B_{20\%}$
Above F_{MSY}	Depleted 0.05%	Depleting 0.0%
Below F_{MSY}	Recovering 0.70%	Sustainable 99.24%

5.5. Stock status: Gulf of Carpentaria

Based on the evidence provided, the status of stock has been classified as **Sustainable**.

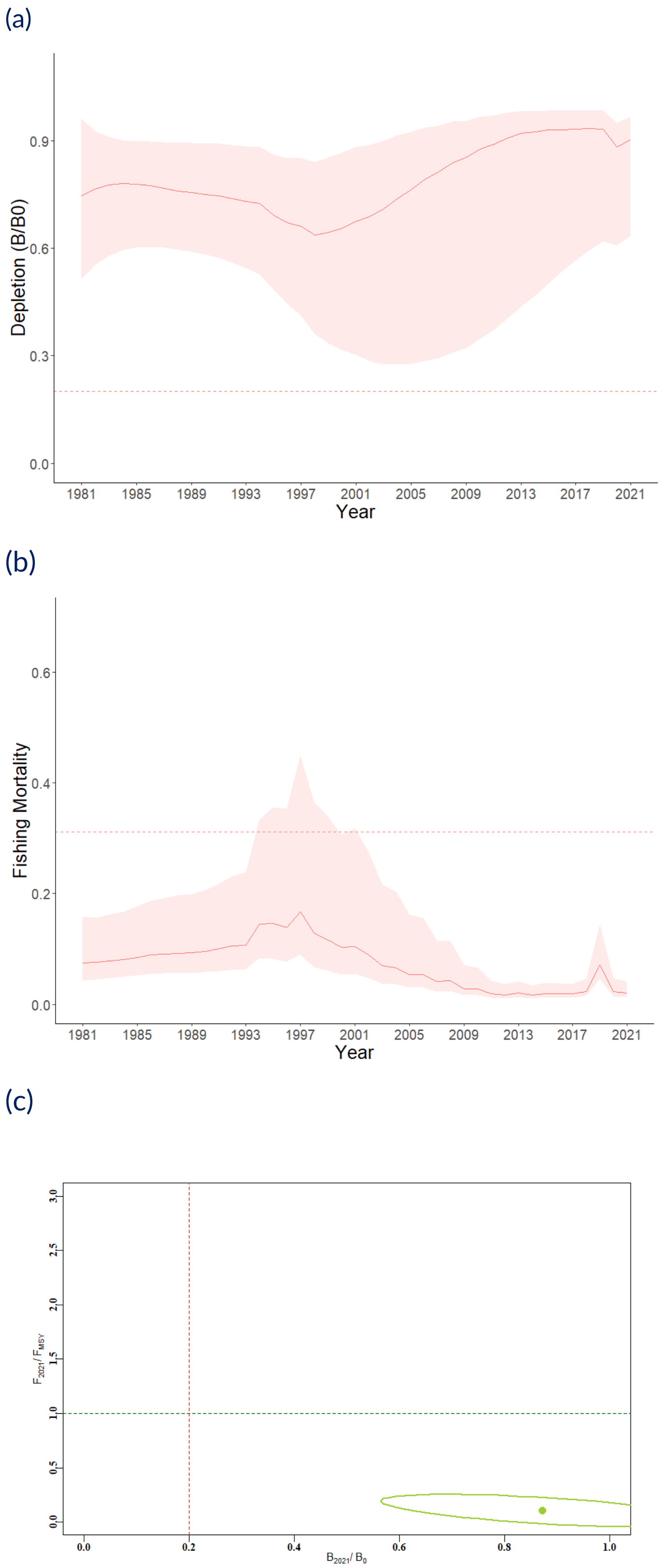


Figure 25: Catch-MSY outcome for Golden Snapper assessment in the Gulf of Carpentaria assessment unit (a) depletion of stock biomass since 1970 assuming 50-99% initial depletion, dotted line indicates 20% of unfished level with ~95% asymptotic intervals (b) trend of fishing mortality between 1970 and 2021, dotted line indicates the limit value F_{MSY} with ~95% asymptotic intervals (b) phase plot indicating the status of fish stock in 2021 relative to the reference points. The ellipse indicate the 95th percentile boundary of stock position from 20,000 model runs.

6. Conclusion

Assessment of Golden Snapper in the Northern Territory is presented across three assessment units.

The model for the Greater Darwin Region estimated that biomass has declined significantly from 1970 to 2015. A decline in fishing mortality since 2010 has resulted in an increasing trend in biomass. However, the median biomass in 2021 is estimated at 21% of the unfished level, with the confidence interval ranging from 13% to 29%. The median fishing mortality relative to MSY in 2021 is estimated at 2.1, with the confidence interval ranging from 1.35 to 2.82. This level of fishing mortality is expected to prevent any further recovery.

On the basis of the evidence provided above, Golden Snapper in the **Greater Darwin Region** is classified as **Depleting**.

The Regional Northern Territory assessment unit is data limited and has been assessed using multiple lines of evidence. Outcomes of Catch-MSY modelling and harvest fractions derived from a fishery independent survey provide evidence for the sustainability of Golden Snapper in this assessment unit. The Catch-MSY model determined that the median biomass remained stable between 78 and 85% of unfished level for the last 20 years with no significant change in fishing pressure during this period. The model shows that the median biomass in 2021 is estimated at 84% of unfished level, with the confidence interval ranging from 39% and 95%. A fishery independent survey indicates that the harvest fraction of Golden Snapper in 2021 is 1.9% of the estimated biomass with a confidence interval from 1.1% to 6.9% of the estimated biomass.

On the basis of the evidence provided above, Golden Snapper in **Regional Northern Territory** are classified as **Sustainable**.

The Gulf of Carpentaria assessment unit is data limited and has been assessed using multiple lines of evidence. Outcomes of Catch-MSY modelling and harvest fractions derived from a fishery independent survey provide evidence for the sustainability of Golden Snapper in this assessment unit. The Catch-MSY model determined that the median biomass remained stable at around 75% of unfished level until 1992 and an increase since late 1990's as a consequence of reduction in catch. The model shows that the median biomass in 2021 is estimated at 90% of unfished level, with the confidence interval ranging from 60% to 97%. A fishery independent survey indicates that the harvest fraction of Golden Snapper in 2021 is 0.59% of the estimated biomass with a confidence interval from 0.34% to 2.1% of the estimated biomass.

On the basis of the evidence provided above, Golden Snapper in the **Gulf of Carpentaria** are classified as **Sustainable**.

7. Options to improve assessments

7.1.1. Greater Darwin Region

There were a number of limitations encountered in assessing Golden Snapper in the Greater Darwin Region. Firstly, there was insufficient information to estimate growth and maturity parameters in the assessment. Improved collection of biological information (e.g. length, weight and age) would be required to estimate those parameters in future assessments. Secondly, the main source of mortality for this assessment unit (i.e. recreational sector catch) is reconstructed from periodic surveys and projections based on population data. Finally, known errors in FTO reporting results in uncertainty in the estimate of mortality from this sector and is a confounding variable in the use of CPUE as an indicator of abundance.

Options to improve future assessments include:

- Conditional age-at-length data by sex and by fleet (sector) would improve the assessment significantly by enabling the estimation of growth and maturity, and selectivity parameters within the model.
- Sex-specific maturity parameters are available from 2010 (NT Fisheries unpublished internal records). However, more recent data on the maturity profile of this species along with sex specific size composition data would help understand how the population has responded to high fishing pressure in the Greater Darwin Region.
- Estimated annual catch for the current assessment is re-constructed from NT recreational surveys that occur every two or three years. Future surveys will continue to provide estimates of recreational catch. However, innovative approaches to improve estimates of catch should also be explored.
- Improved reporting in FTO logbooks and improved validation across the entire fleet.
- CPUE, length and age composition from fishery independent surveys would provide independent sources of data for future assessments.

7.1.2. Other assessment units

The improvement options below are specific to the Regional Northern Territory and Gulf of Carpentaria assessment units as they have similar data sources and challenges:

- The majority of catch removals from this assessment unit are attributed to demersal trawlers, suggesting the potential for developing and standardising a fishery-dependent CPUE index. Incorporating CPUE could build confidence in assessments, facilitating the transition from Catch-MSY to other methods that utilize additional data.
- Ongoing fishery independent surveys would facilitate developing a time series of abundance for Golden Snapper stocks in both assessment units. Continuation of 2021 trawl biomass survey (Knuckey and Koopman, 2022) would generate such an index[3].
- Length/age composition data (for example collected through observer trips on board trawler or trap fisheries offshore) would inform the population size structure in future assessments. Such data are also useful for catch and length only assessments if a reliable CPUE index is not available, particularly for lightly exploited fish stocks.

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[3] The authors note that the trawl-based fishery independent survey's objective is to provide an estimate of relative abundance for species other than Golden Snapper. For this reason, Golden Snapper would not form a primary reason for undertaking future surveys, rather an index of abundance for this species from the surveys would be considered an additional benefit.

Appendix A: Glossary of abbreviations and terms

B_{2021}	Stock biomass in year 2021
$B_{20\%}$	20% of virgin biomass levels
CV	Coefficient of Variation
CPUE	Catch Per Unit Effort
DF	Demersal Fishery
F	Fishing mortality rate
FRDC	Fisheries Research and Development Corporation
GOC	Gulf of Carpentaria
h	Steepness in stock-recruitment indicating resilience of the species
K	Kappa/VBGF growth parameter
L_{∞}	Asymptotic length (VBGF parameter)
M	Natural mortality rate
MSY	Maximum Sustainable Yield
NT	Northern Territory
S	Population proportion of survival from natural mortality
SRA	Stock Reduction Analysis
SS-DL	Stock Synthesis – Data Limited
t	tonne
t_0	Age at length zero
TACC	Total Allowable Commercial Catch
TRF	Timor Reef Fishery
F_{2021}	Fishing mortality in 2021
F_{MSY}	Fishing mortality to achieve MSY
U	Annual Exploitation
VBGF	Von Bertalanffy Growth Function
Z	Total mortality rate

Appendix B: GLM standardisation of CPUE- Greater Darwin

Catch Per Unit Effort

Fishing Tour Operator (FTO) logbook data on catch of Golden Snapper (in numbers) and effort (hours fished multiplied by number of anglers) per fishing event were used to develop a GLM model. Fishing event is a single angling session that would have details of the date of fishing (year and month), number of anglers, spatial grid of the fishing location and the duration of fishing in minutes.

To ensure the use of meaningful data, the following steps were taken:

- The data is filtered for fishing events where the fisher has declared to be ‘ReefBottom’ fishing which would exclude all events that are not targeted at reef species, i.e. ‘Barramundi’, ‘Crabbing’ and ‘Game’ fishing.
- Fishing events with catch records of no Golden Snapper (zero catch) were retained and this accounted for 25% of the raw data.
- Catch Per Unit Effort of Golden Snapper is computed for each fishing event as:

$$CPUE = \frac{Catch\ numbers}{Fishing\ duration\ X\ Number\ of\ anglers}$$

- The CPUE is computed to use as the response variable in the GLM model.
- The year, month and spatial grid are converted into categorical variables to use as covariates (explanatory) in the GLM model.

The GLM model

The CPUE was standardised using a hurdle based model i.e., Zero Altered Gamma –ZAG where the absence/presence of Golden Snapper in a fishing event is analysed with a Bernoulli GLM and the non-zero catch records of Golden Snapper is analysed with a Gamma GLM using the ‘glmmTMB’ package (Brooks et al., 2017).

```
glmmTMB(CPUE~CY+MONTH+GRID_CODE,
        family = ziGamma(link="log"),
        ziformula = ~1+CY+MONTH+GRID_CODE,
        data=CPUE_data)
```

Model summary

The model summary is provided below. Please note the entire model summary output is not provided due to page limit constraint.

```
Family: Gamma  ( log )
Formula:          CPUE ~ CY + MONTH + GRID_CODE
Zero inflation:        ~1 + CY + MONTH + GRID_CODE
Data: CPUE.FTO

     AIC      BIC   logLik deviance df.resid
-57825.6 -56992.7  29009.8 -58019.6    39485


Dispersion estimate for Gamma family (sigma^2): 1.41

Conditional model:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)   -1.96521    0.16277 -12.074  < 2e-16 ***
CY1995         0.09317    0.11388   0.818 0.413262
CY1996         0.14594    0.10727   1.360 0.173688
CY1997         0.51440    0.09800   5.249 1.53e-07 ***
......
......

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Zero-inflation model:
               Estimate Std. Error z value Pr(>|z|)
(Intercept)   -0.968831   0.250394  -3.869 0.000109 ***
CY1995         0.443178   0.179679   2.466 0.013644 *
CY1996         0.662027   0.168134   3.938 8.23e-05 ***
CY1997         0.764700   0.155981   4.903 9.46e-07 ***
......
......
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Model choice and diagnostics

A large range of models were tested before selecting the ZAG model. The selection is based on multiple criteria such as Akaike Information Criterion (AIC), dispersion and residual patterns. The models are also tested for zero inflation using ‘DHARMa’ R package (Hartig, 2022), which provides a histogram of the predicted number of zero records and a red line indicating the actual number of zero records in the data set (Figure B 1).

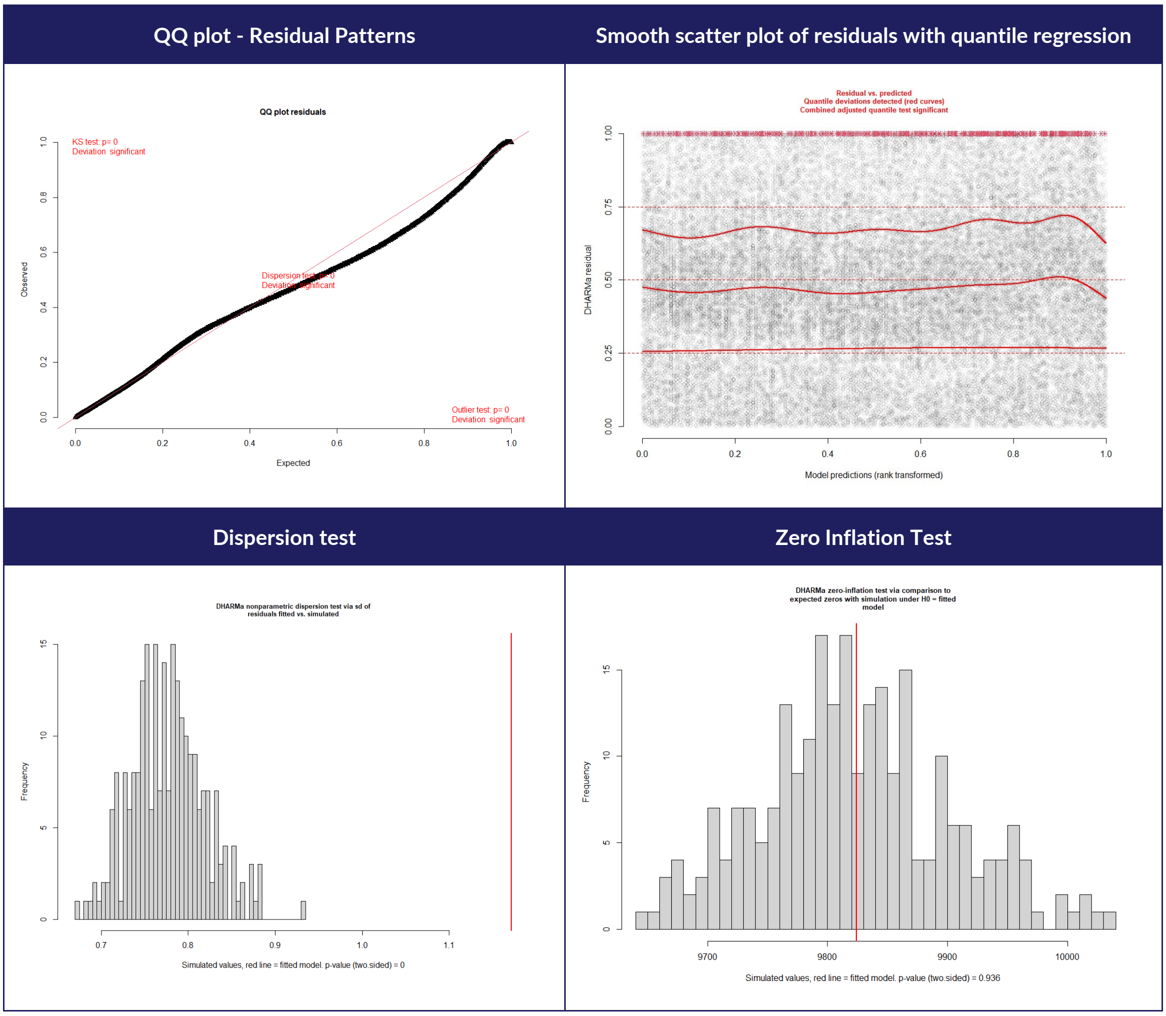


Figure B 1: Characteristics of the ZAG - GLM model used for standardising abundance index (CPUE) of Golden Snapper catch in the Greater Darwin Region

Computation of relative index of CPUE for stock assessment

The annual trend in CPUE is predicted using the ZAG hurdle model by keeping all explanatory variables constant except 'Year'. This is employed by using the '*predict*' function in R statistical software (R Core Team, 2024). Further, the predicted CPUE values are 'scaled' dividing through by the mean of the time series. This sets the average value to 1.0, which permits simple visual comparison with other time-series.

Coefficient of variation for CPUE

Stock Synthesis Data Limited (SS-DL) requires the user to provide coefficient of variation (CV) associated to CPUE values in the time series. This is achieved by fitting a smooth curve using a locally estimated scatterplot smoothing (aka LOESS) nonparametric method (the '*loess*' function in R statistical software). No assumptions are made about the underlying structure of data. The degree of smoothing was set to α=0.3. The coefficient of variation is computed using the fit and standard error from predicted values of the LOESS model.

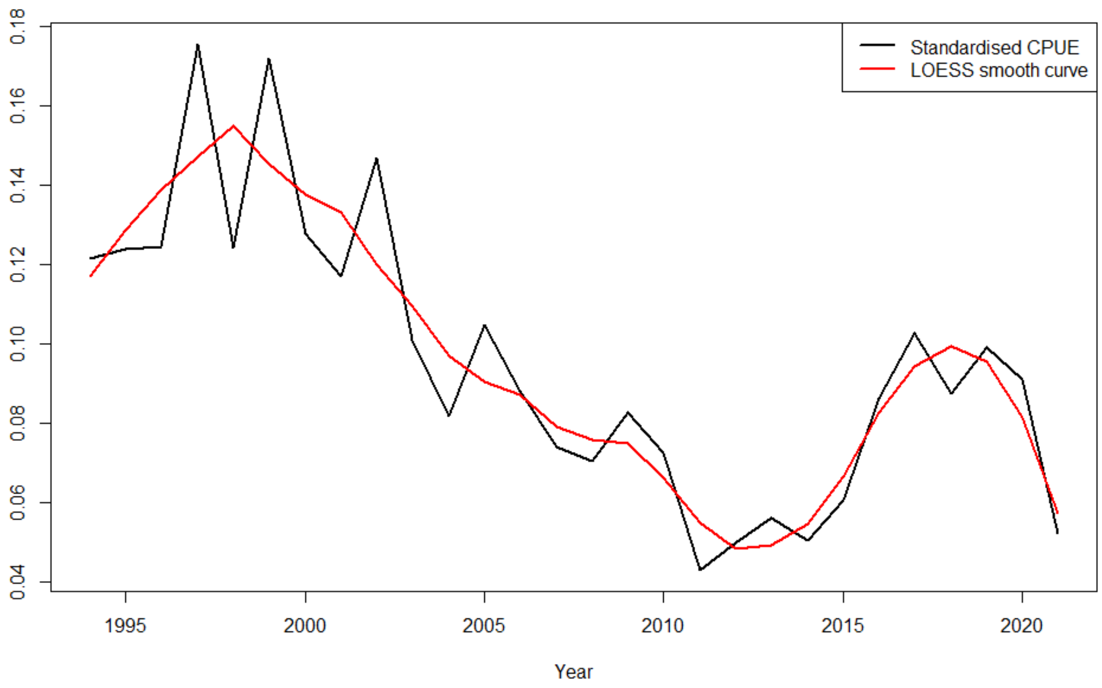


Figure B 2: Standardised CPUE and the smooth curve fitted using LOESS

Appendix C: Diagnostics of reference model – Greater Darwin

Appendix C 1: Model Convergence

STEP 1: Parameters were not estimated at a bound.

Three set of parameters were estimated within the model:

1) Initial stock scale by estimating the log of virgin recruitment (lnR0)
2) Selectivity parameters for the Fishing Tour Operator sector
3) Selectivity parameters for the recreational sector

None of the parameters were estimated near or at the bound. Table C 1 shows parameters that were estimated and pre-specified in the reference model.

Table C 1: Model parameters outcomes of reference model in Stock Synthesis

Parameter	Type	Value	Minimum	Maximum	Initial value	Prior Type
Virgin recruitment, Ln(R0)	Estimated	5.661	0.0001	20	12	No Prior
Selectivity, size at inflection - FTO	Estimated	2.96	-4	12	2.96	No Prior
Selectivity, 95% selection - FTO	Estimated	36.68	11.5	81	36.68	No Prior
Selectivity, size at inflection - Recreational	Estimated	4.01	-4	12	4.01	No Prior
Selectivity, 95% selection - Recreational	Estimated	37.17	11.5	81	37.17	No Prior
Natural Mortality, *M*	Pre-specified	0.255				
Age at length 0, t_0	Pre-specified	-0.483				
Asymptotic length, L_∞	Pre-specified	67				
VBGF Growth, *k*	Pre-specified	0.2539				
Steepness, *h*	Pre-specified	0.7				

STEP 2: The final gradient is relatively small and hessian matrix is positive definite (Table C 2)

Table C 2: Final gradient, hessian and the total log likelihood from the converged reference model

Scenario	Final gradient	Hessian	Total Log likelihood
Scenario 2/reference model	6.79237e-05	150.524	6.63355

STEP 3: Correlation matrix of highly correlated parameter pairs were examined and none of them were above 0.95 (in absolute value).

STEP 4: The models converge to a "global" solution.

Jitter test

A jitter test is conducted to determine whether models are sensitive to the initial parameter values and that the model converged to a global minimum rather than at local minimum. Jitter analysis is a technique used to test the optimality, robustness and stability of the maximum likelihood estimate obtained for a particular model. This involves randomly changing the starting values used for all estimated parameters and re-running the model, to test what alternative solutions may be found by the optimisation algorithm from different initial locations, which is sometimes referred to as sensitivity to initial conditions. Two diagnostics are of interest with a jitter analysis, a check on whether a better "optimal solution" may be found, with a higher likelihood value, and also to see how frequently the optimal solution is found. As all estimated parameters are randomly modified, or "jittered," simultaneously, this can sometimes result in a model either failing to converge or finding a local maximum in a different (suboptimal) part of the multi-dimensional parameter space. A jitter analysis was conducted with 100 replications, modifying initial parameter values by 10%. Jittering was implemented in the SS-DL tool (Cope, 2023). The jitter test did not provide evidence to reject the hypothesis that the parameter optimization converged to a global solution (Figure C 1).

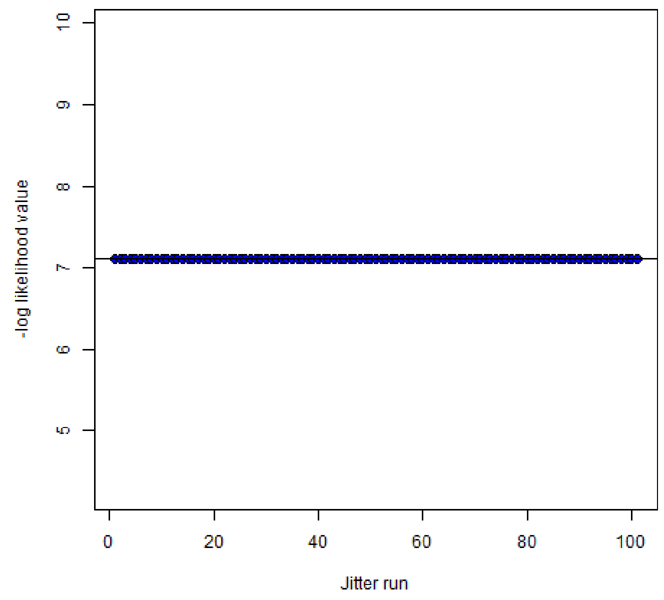


Figure C 1: Log-likelihood estimates of reference model that converged during the jitter analysis.

Appendix C 2: Goodness of fit

Three methods are used to evaluate the goodness of fit of the model. The first method plots residuals to observe trends, patterns, and variation in fits to the data over time using the R package 'ss3diags' (Carvalho et al., 2017). A random distribution of residuals will fall below or above the median 50% of the time. The presence of temporal auto-correlation in residuals is evident by systematic drifts in the residual's mean throughout time. A good data fit to the model would have random distribution of residuals below or above the median 50% of the time (Figure C 3, Figure C 2).

Root Mean Square Error

The second common goodness-of-fit statistic used as a diagnostic is the root mean square error (RMSE; Carvalho et al., 2017) which describes the standard deviation of residuals, such that:

$$RMSE = \sqrt{\frac{\sum_t (\hat{y}_t - y_t)^2}{n}}$$

Where $\hat{y}_t$ is the predicted value at the time step t, y_t is the observed value, and n is the number of observations. A relative small RMSE (30%) indicates a reasonably precise model fit to relative abundance indices (Winker et al., 2018).

Table C 3 shows the RMSE score obtained for the model fit to the relative abundance index and estimated mean length. Results indicate a good fit to the abundance index and mean length estimates (Figure C 2).

Table C 3: Root Mean Square Error indicating the Goodness-of-fit statistic of reference model.

Type	Sector	Root Mean Square Error (RMSE)	Number of observations
Abundance Index	FTO	18%	28
Mean Length	FTO	5.2%	11
Mean Length	Recreational	1.6%	5

(a) (b)

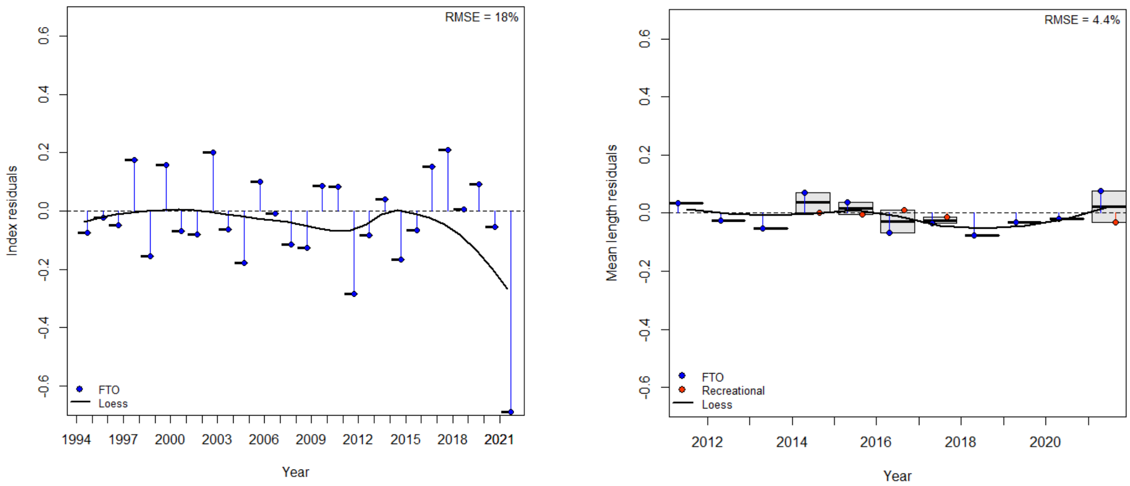


Figure C 2: Joint residual plots for (a) annual mean CPUE residuals from FTO sector and (b) annual mean length residuals by multiple fishing fleets/sectors from the reference model. Solid black line show loess smoother through all residuals. Box plots indicate the median and quantiles in cases where residuals from the multiple sectors are available for any given year.

Runs test

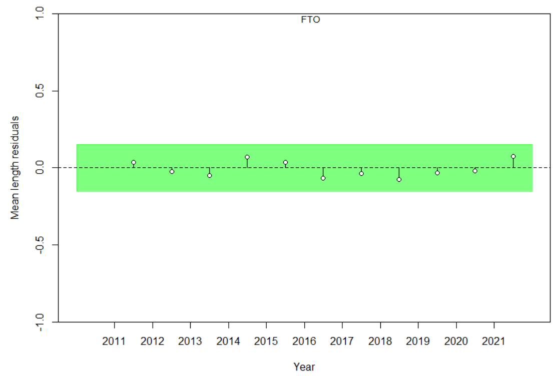
The third method is the Wald-Wolfowitz runs test (Wald-Wolfowitz 1940), hereafter termed the “runs test”. The runs test is a non-parametric test that evaluate the null hypothesis that the elements of a sequence are not independent from each other. We specify an $\alpha = 0.05$ threshold when applying the runs test to the reference model residuals. To assist in interpretation, green shading on the figure presenting the time series of residuals indicates the runs test has passed (randomly distributed time series of residuals, p≥0.05), while red indicates it has failed (p<0.05).

There was no evidence (p ≥0.05) to reject the hypothesis of randomly distributed residuals for the abundance index fit (FTO) and mean length fit (FTO and recreational sector), that all data points fell inside the three-sigma limit (Table C 4 and Figure C 3).

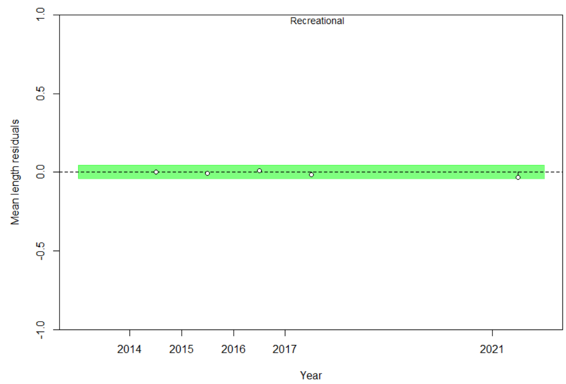
Table C 4: Runs test indicate no residual patterns for the model fits of the reference model in Stock Synthesis.

Fishery	p-value	Test	Lower limit	Upper limit	Type
FTO	0.603	Passed	-0.4379633	0.4379633	Abundance Index
FTO	0.225	Passed	-0.1505434	0.1505434	Mean Length
Recreational	0.744	Passed	-0.0427322	0.0427322	Mean Length

(a)



(b)



(c)

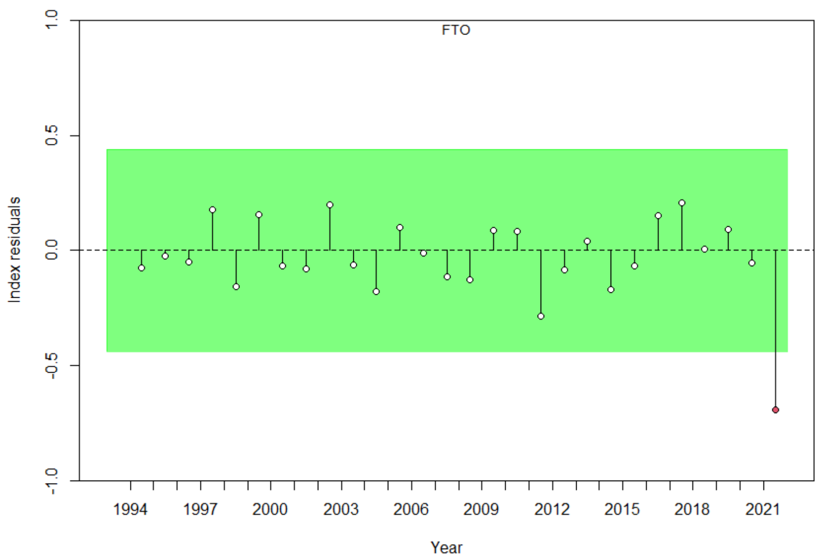


Figure C 3: Runs tests results illustrate (a) CPUE fit; mean lengths of size composition data of (b) FTO sector and (c) recreational sector. Green shading indicates no evidence to reject the hypothesis of a randomly distributed time series of residuals. The shaded area spans three residual standard deviations to either side from zero.

Appendix C 3: Model consistency

Likelihood profiles

Likelihood profiles are most often used to obtain the 95% confidence intervals for a parameter of interest (Punt, 2018) and can be used to evaluate whether there is evidence to support fixing a parameter at a chosen value. If an estimated parameter is within the range of the 95% confidence interval of the total likelihood profile there is no support from the data to pre-specify the value. If the pre-specified value is outside the 95% confidence interval and there is evidence that the data holds information about this parameter, it would be reasonable to ask why the parameter was pre-specified and not estimated. If the value is to be pre-specified it must be justified as to what basis should inconsistency with the data be ignored.

Integrated stock assessments, such as SS, include multiple data sources that may be in conflict due to inconsistencies in sampling or more commonly owing to incorrect assumptions (e.g. assuming that catch-rates are linearly related to abundance or model misspecification). Therefore, likelihood profiles can be used as a diagnostic tool to identify these data conflicts (Punt, 2018).

A parameter profile is constructed by sequentially fixing a range of values and running the model to estimate the total and data-component likelihoods. Likelihood profiles have been constructed for $Ln(R_0)$, natural mortality (*M*), steepness (*h*) and asymptotic length (L_∞). Results show that the length component from FTO sector seem to be more informative for $Ln(R_0)$. However for all other parameters, the minimum negative likelihood go to the bounds of the profile indicating there is limited information available to estimate those parameters or significant conflicts are present (Figure C 4,Figure C 5, Figure C 6 and Figure C 7).

Likelihood profile for virgin recruitment (R_0)

The virgin recruitment at equilibrium (R_0) is a commonly profiled parameter in integrated models as it represents an ideal global scaling parameter that is proportional to the unfished biomass (Wang et al., 2014). The likelihood profile of $ln(R_0)$, is shown in Figure C 4 with the total likelihood shown in black and components of the total likelihood from different data sources shown in a range of colours. $Ln(R_0)$ is well estimated by the likelihood profile at 5.79 with 95% confidence intervals of $ln(R_0) = 2$ to $ln(R_0) = 14$ (Figure C 4, left top panel).

The length data is the most influential on the total likelihood, with similar minimum values to the total likelihood. The contribution from each fleet to the likelihood components shows that length data component from FTO and recreational sector suggest similar $ln(R_0)$ to the total value.

There is some conflict in the CPUE (index/survey likelihoods) for the FTO sector suggesting a lower $ln(R_0)$=4.3 (Figure C 4, bottom right panel).

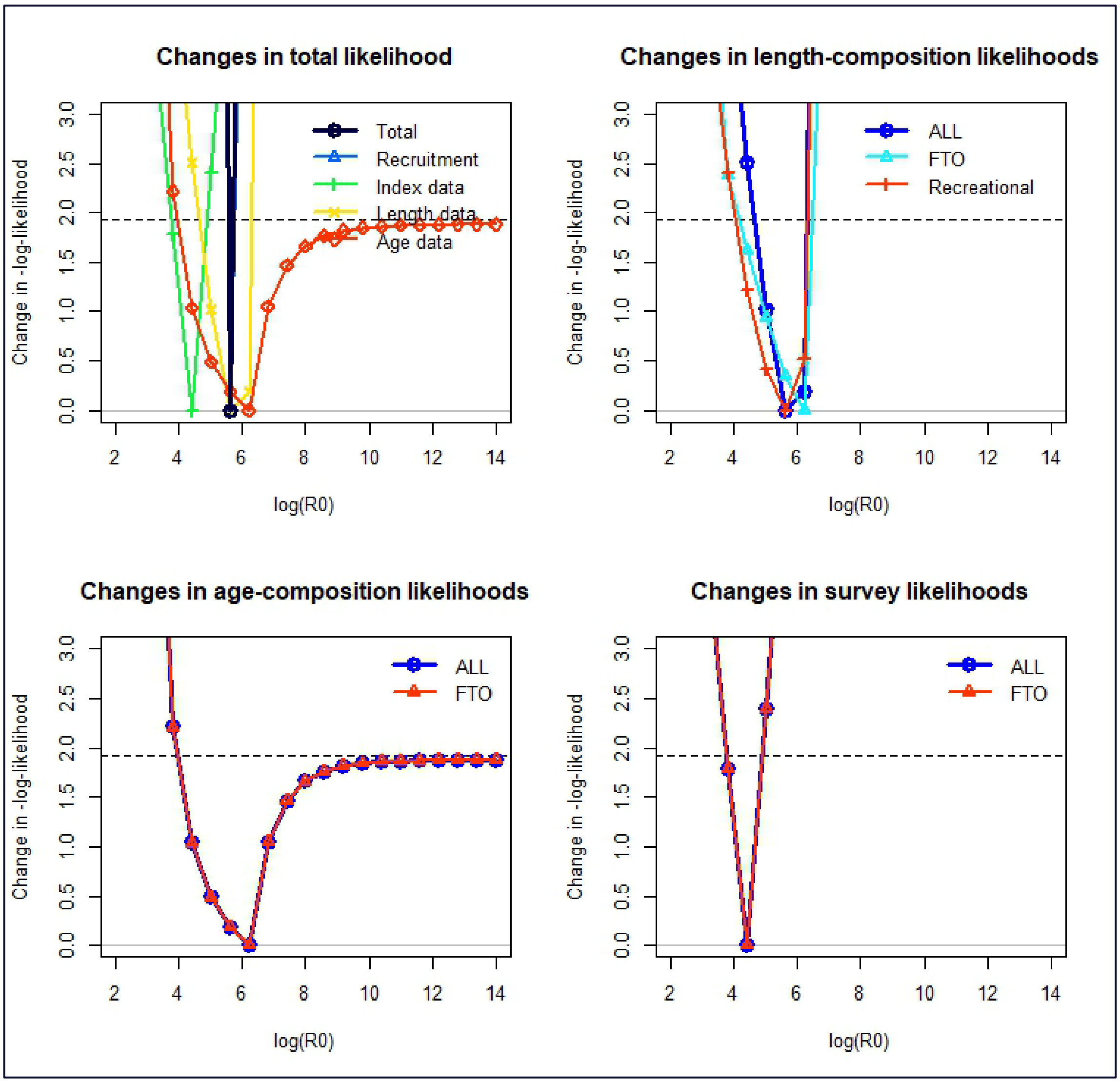


Figure C 4: The likelihood profile for virgin recruitment *ln(R₀)* ranging from 2 to 14. Values above 95% confidence limits (dashed line) are irrelevant information on the likelihood profile.

Likelihood profile for natural mortality (*M*)

The likelihood profile for natural mortality, *M*, is shown in Figure C 5. The total likelihood with priors is shown in black, the total likelihood without priors in the dashed line and components of the total likelihood from different data sources shown in a range of colours. The age composition likelihood profile indicates *M* is less than 0.2, while the length composition profile indicates that *M* is approximately 0.55. The survey data indicates an *M* value of 0.6 and appears uninformative. The results indicate that there are significant conflicts in the data with regard to *M*. Estimation of this parameter would be considered uninformative in the context of these conflicts.

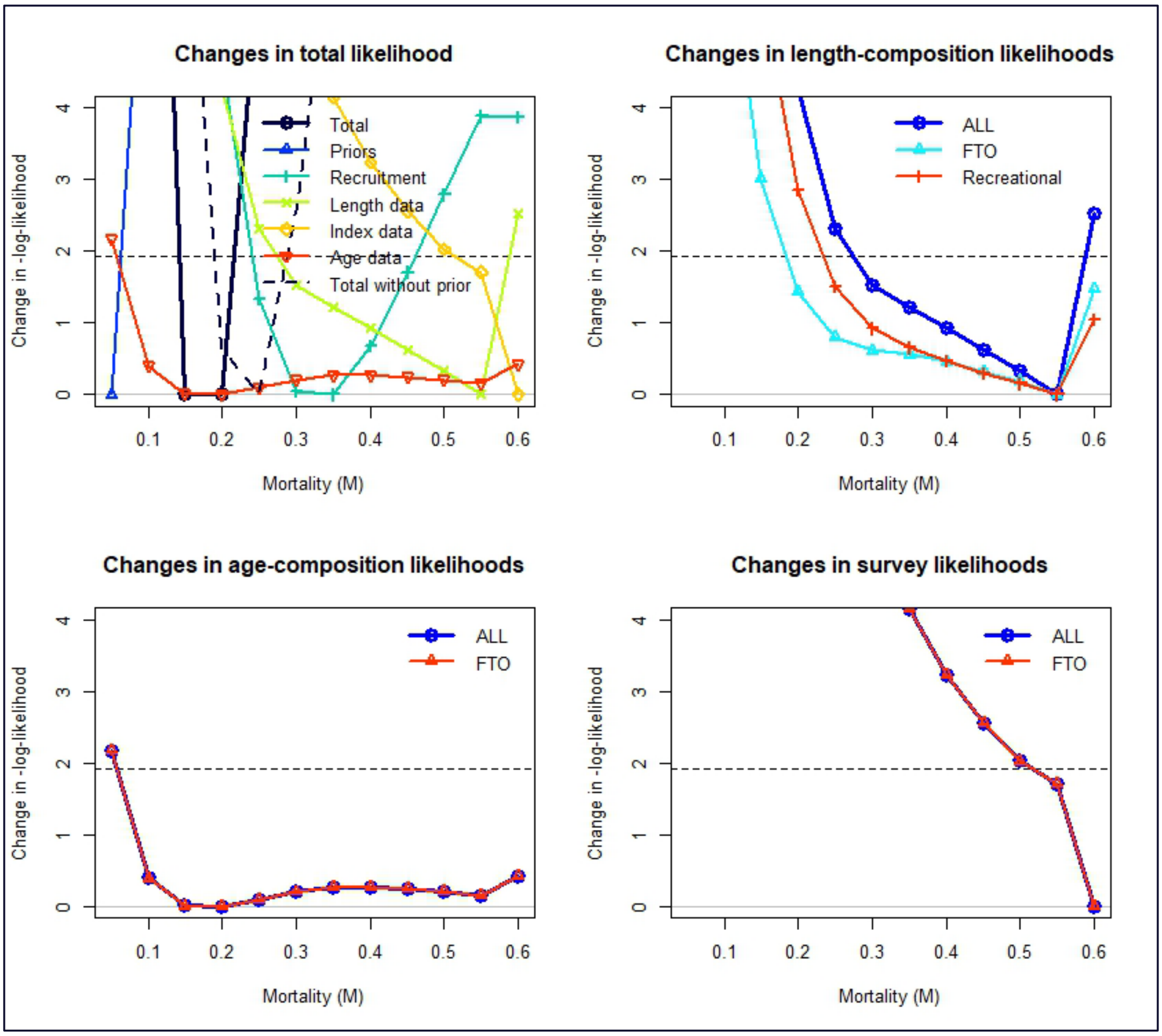


Figure C 5: The likelihood profile for natural mortality (*M*) ranging from 0.05 to 0.6. Values above 95% confidence limits (red dotted line) are irrelevant information on the likelihood profile.

Likelihood profile for steepness (*h*)

The likelihood profile on stock recruitment steepness (*h*) displays the total likelihood in black, with various components from different data sources shown in a range of colours (Figure C 6). The figure shows that *h* is not well defined, it is therefore reasonable to fix *h* at 0.7, the default value assumed in the reference model. Overall, length-composition, age data and the index likelihoods also show that *h* is uninformative, where the negative likelihood reduces progressively with higher values of steepness (Figure C 6).

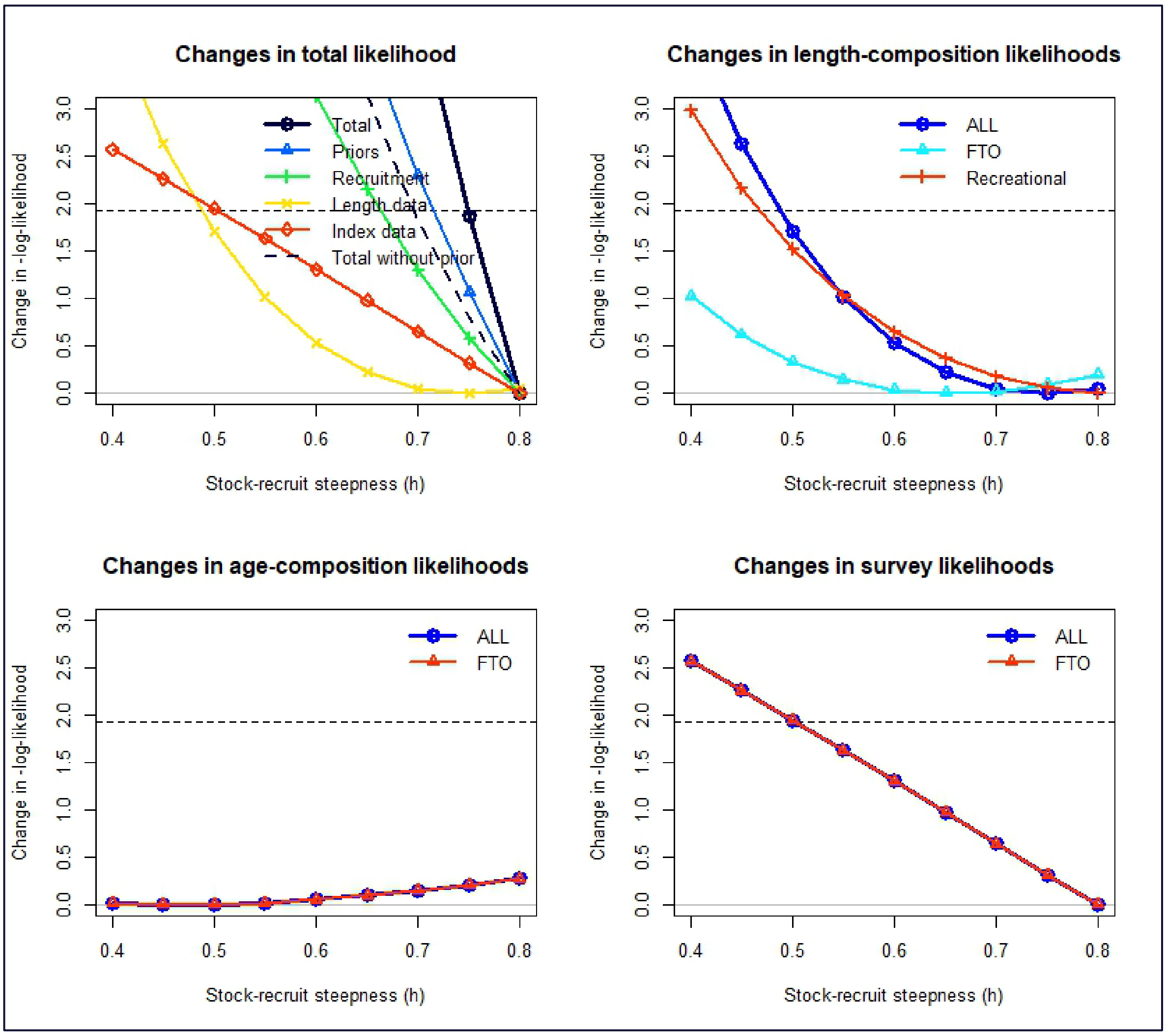


Figure C 6: The likelihood profile for steepness (*h*) ranging from 0.4 to 0.8. Please note values above 95% confidence limits (dashed line) are irrelevant information on the likelihood profile.

Likelihood profile for asymptotic length (L_∞)

Asymptotic length is estimated by the likelihood profile at L_∞= 78 cm with 95% confidence intervals of L_∞= 50 cm to L_∞= 130 cm (Figure C 7). The length and recruitment data are most influential on the total likelihood, with similar minimum values to the total likelihood. The length data component of FTO and recreational sectors suggest a range of 78 cm to 90 cm of L_∞. There is some conflict in the data with the index data suggesting a higher L_∞= 130 cm while the age data suggest a range of 50 to 83 cm of L_∞ (Figure C 7).

Age composition likelihood for the FTO suggests a wide range of L_∞ in comparison with values suggested by the total likelihood, although there is little information in this data (Figure C 7, bottom left panel). The CPUE (labelled as survey likelihoods) prefers a higher L_∞, although again there is little information in the CPUE index (Figure C 7, bottom left plot).

Overall, the likelihood profile of L_∞ show apparent data conflict across all sources of data.

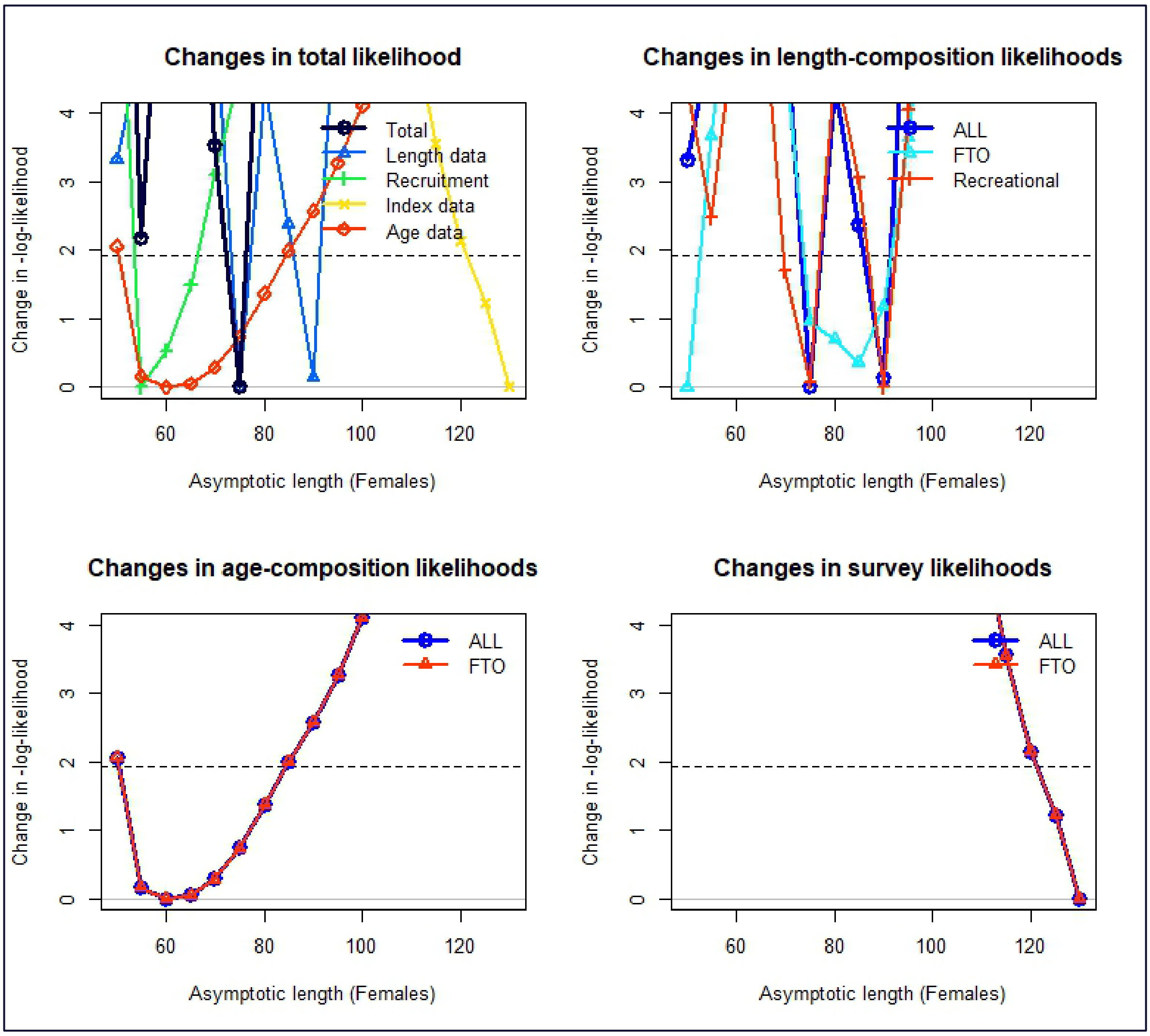


Figure C 7: The likelihood profile for asymptotic length ($L\infty$) ranging from 50cm to 130cm. Please note values above 95% confidence limits (red dotted line) are irrelevant information on the likelihood profile.

Retrospective analysis

A retrospective analysis (Cadrin and Vaughan, 1997; Mohn, 1999) has been undertaken to identify whether assessment outcomes change as data is removed from the assessment. The retrospective analysis was undertaken using the following procedure:

1) One year of data was removed sequentially from the 2021 model, while maintaining the same assumptions and tunning;
2) Time dependent model parameters (e.g. the last year of estimated recruitment) were changed to be one year earlier;
3) The model was run to determine stock status estimates when less data is available (i.e. in the past);
4) Steps 1–3 were repeated five time (i.e. sequentially removing five years of data).

Trends in biomass, stock status, fishing mortality and recruitment are then examined to help understand how reliable the assessment is at estimating the relative biomass in recent years.

The severity of retrospective patterns can be quantified using Mohn's rho (ρ_M), which is defined as the average of relative differences between an estimate from assessment using a truncated time series and an estimate from assessment using the full time series (Hurtado-ferro et al., 2015). Mohn's rho values are calculated for a range of quantities, including spawning biomass, recruitment, *F* and stock status. As a general rule of thumb, values of Mohn's rho that fall outside -0.22 to 0.30 for shorter-lived species indicates an undesirable retrospective pattern or cause for concern in an assessment (Hurtado-ferro et al., 2015).

The ρ_M for the biomass relative to unfished levels is 0.72 indicating some retrospective patterns if data are removed from the terminal years i.e., up to 5 years from 2021 until 2016 (Table C 5). The estimated fraction of unfished biomass increases consistently over subsequent peels, which indicates that the biomass estimates are positively biased (Figure C 8). Although ρ_M fall outside the range of accepted values (-0.22 to 0.30), all retrospective patterns indicate that the status of the stock in Greater Darwin Region is likely depleting or depleted.

Table C 5: Mohn's rho values from retrospective analysis of reference model

Biomass	Biomass relative to unfished	Recruitment	Fishing Mortality
0.782	0.721	-0.703	-0.794

An alternative presentation of the retrospective analysis is applied to the recruitment time series as a 'squid plot' (Figure C 9). Squid plots track changes in recruitment deviations for specific cohorts as the last five years of data are successively removed. Each coloured string represents a cohort and includes up to six points: one for the reference model using data up to 2021 and one for each of the five different retrospectives. The strings can be followed from right to left as data from successive years is removed. Changes in recruitment deviation estimates, as each year of data is removed, are reflected by changes on the y-axis. A negative value indicates an upward revision, while a positive value indicates a downward revision relative to the most recent estimate. Large changes on the y-axis suggest significant revisions. If all changes share the same sign (positive or negative), it may indicate a trend in one direction, potentially pointing to bias rather than random revisions to parameter estimates.

The squid plot for the reference model shows deviations below zero, suggesting that there is a pathological retrospective pattern in recruitment deviation estimates (Figure C 9). This pattern suggest misspecification in the model, however, as recruitment estimates are being revised upwards in a successive assessment i.e., 2020, this pattern is less of a concern.

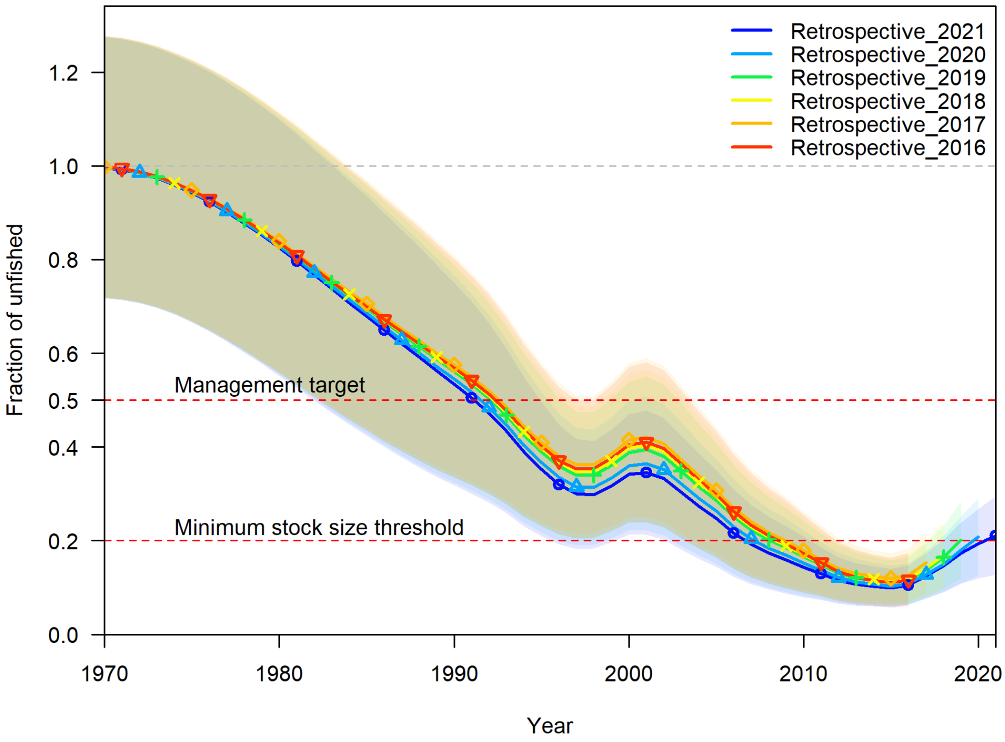


Figure C 8: Retrospective analysis for biomass relative to unfished levels, with data included 2021 (blue) and then successive years removed back to 2016. $B_{20\%}$ is depicted as the minimum stock size threshold.

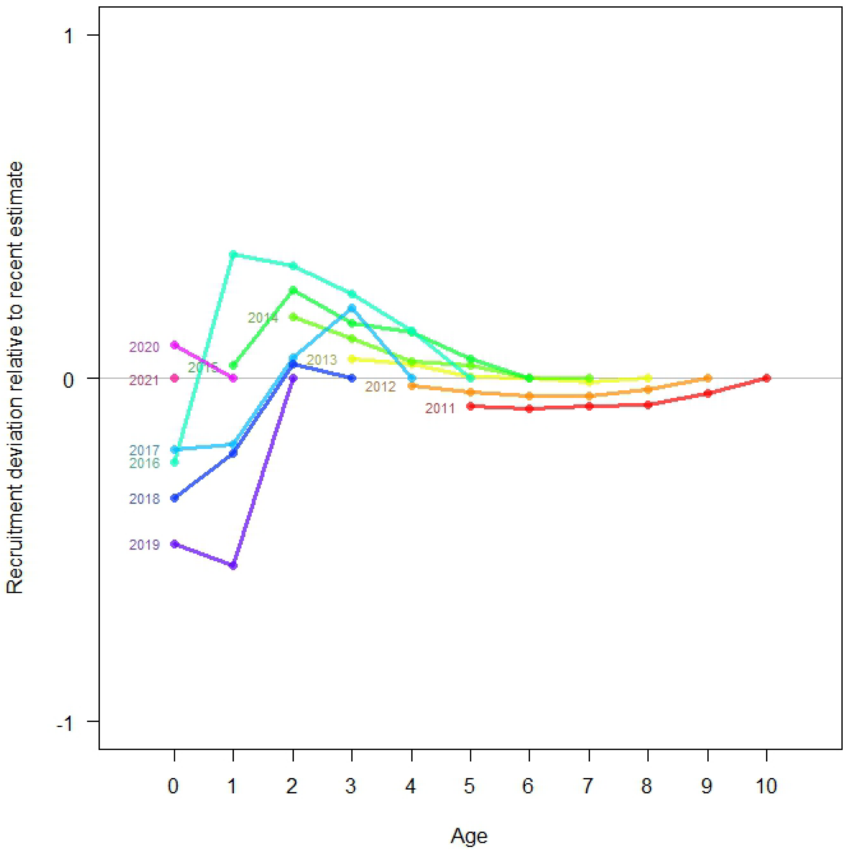


Figure C 9: Retrospective analysis of recruitment deviations (squid plot), with data included 2021 and then successive years removed back to 2016.

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