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Development of a harvest strategy for resource-limited deepwater snapper fisheries

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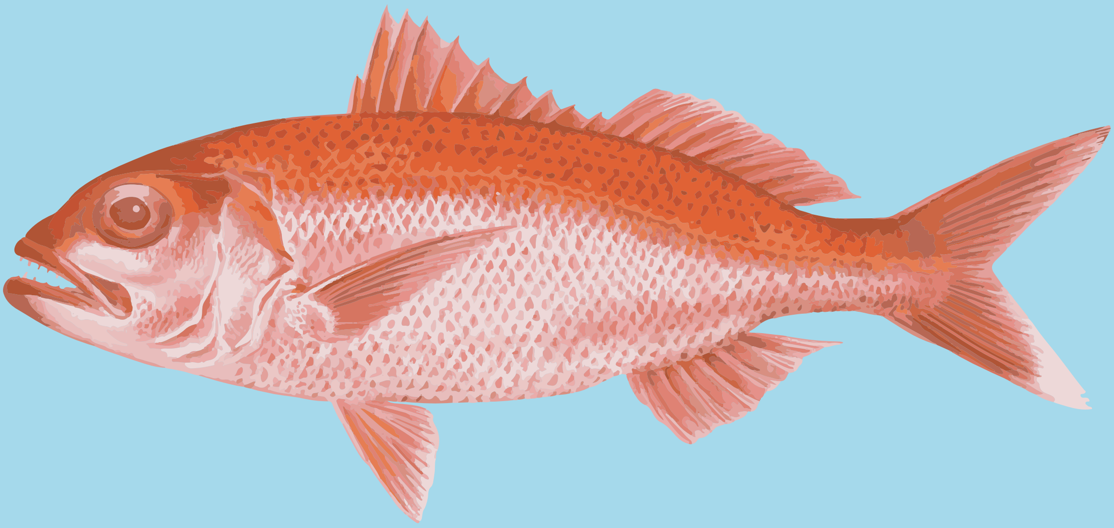


Aim: This fact sheet outlines three alternative stock assessment techniques for deepwater snapper fisheries and examples of their incorporation into a formal harvest strategy.

Background

Deepwater snapper are an important resource for many Pacific island countries and territories (PICTs). Fisheries for deepwater snapper supply domestic and export markets, acting as both a food source and economic commodity. However, a lack of formalised harvest policies for deepwater snapper stocks has resulted in ad-hoc management in many countries.

Within Tonga, the deepwater snapper fishery is the second largest fisheries export behind tuna (Halafihi, 2015). Stock assessments have been conducted by international and regional organisations (Latu and Tulua, 1991; King, 1992; Langi *et al.*, 1992; Latu and Talua, 1992; MRAG, 1994) since the fishery commenced, albeit irregularly, for the purpose of estimating Maximum Sustainable Yield (MSY). These estimates have ranged broadly from ~60-300 tonnes. Declines in catch per-unit effort (CPUE) and total harvest (**Fig. 1**) have been observed, along with a spatial expansion in effort and shifts in species composition (**Fig. 2**). This has raised concerns for the sustainability and economic viability of this fishery.

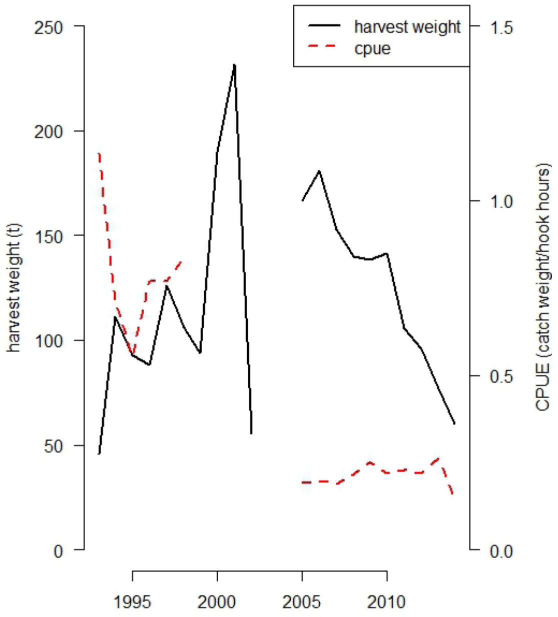


Figure 1: Total harvest weight (t) of deepwater snapper in Tonga and the corresponding catch per-unit effort from 1993-2014.

To appropriately manage stocks, a **harvest strategy** can be formalised to create a decision framework for management. Although traditionally designed for data-rich fisheries, harvest strategies also have been successfully implemented in data-poor scenarios (Dowling *et al*., 2015; Smith *et al*., 2014). Harvest strategies involve:

1. A **monitoring program**;
2. A **formal assessment** estimating stock status against management objectives;
3. **Decision rules** to determine management responses.

Harvest strategies are structured around key **management objectives** for the fishery which have been outlined in Tonga's most recent management plan (Wilson, 2007). These include:

1. To ensure that utilisation of the deep bottom fish resources are for long term conservation and sustainable benefit.
2. To maximise economic welfare to Tonga from utilisation of its deep bottom fish resource including harvesting, processing and exporting.
3. To contribute to the food security and livelihoods of Tongan subjects through sustainable utilisation and employment.

Historically, managers have attempted to apply data-rich assessment techniques to PICTs deepwater snapper fisheries. This has proven challenging due to discontinuous data collection and funding schemes, leading to high levels of uncertainty associated with estimates of stock size and health. Here, we apply three formal assessment options that have been successfully used in data poor fisheries to the Tongan deepwater snapper fishery. We provide a description of the required monitoring programs and examples of potential decision rules that can be derived from these methods.

1. Biomass dynamic model (BDM) for flametail snapper *Etelis coruscans*

Monitoring program

- Weight of catch
- A measure of effort (eg: hook hours, days fishing, reel hours etc.)
- Factors that influence catch rates (eg: depth, location, distance travelled, #hooks/line etc.)

Biomass dynamic models are a common stock assessment technique used to estimate MSY. Harvesting at MSY maintains the population size at the point of maximum growth rate. Fisheries managers often use estimates of MSY to set Total Allowable Catch (TAC) and Individual Transferable Quotas (ITQ) for fisheries to limit the weight of catch harvested.

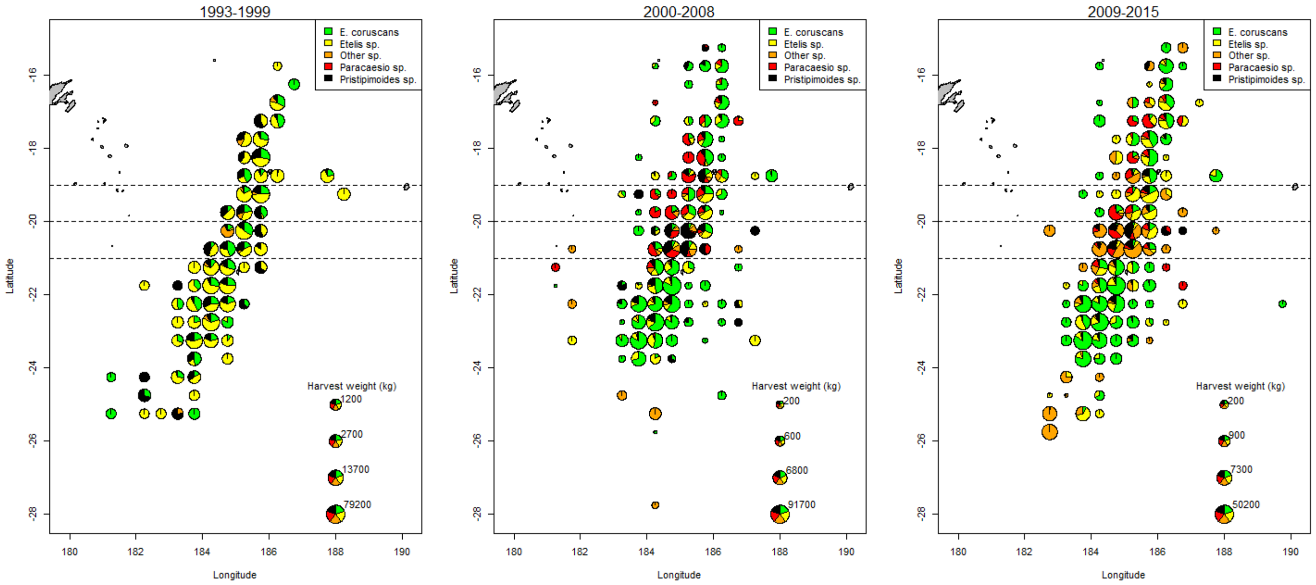
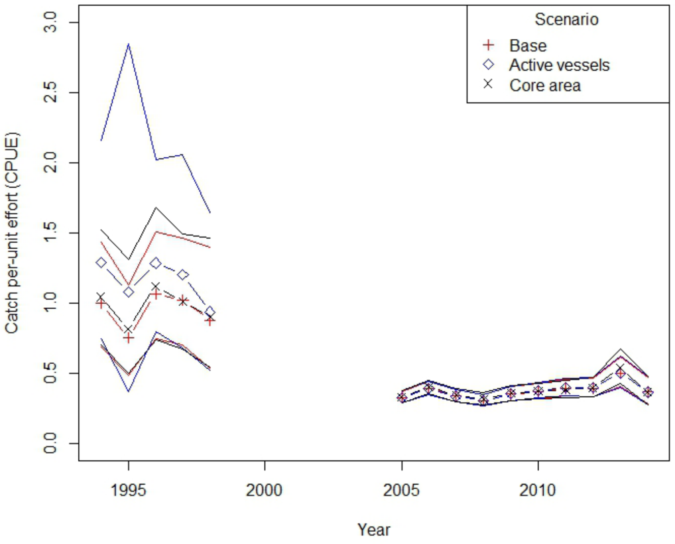


Figure 2: Shifts in species composition and spatial expansion of effort in the Tongan deepwater snapper fishery at 0.5° resolution. Pie radius size determined by total harvest weight (kg) removed from each grid cell across three time periods (1993–1999, 2000–2008, 2009–2015). Species composition is represented by five clusters designated using k-means clustering analysis.



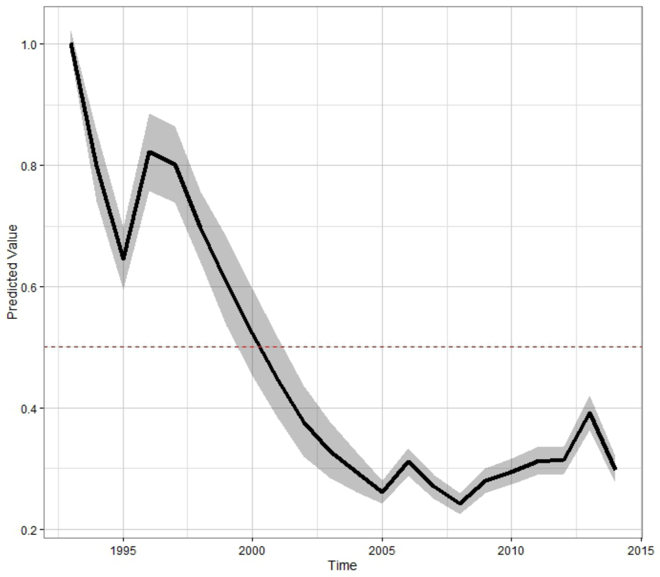


Figure 3: Estimates of standardised catch per-unit effort (CPUE) of *E. coruscans* calculated using harvest weight for three different scenarios.

Figure 4: Predicted stock levels of *E. coruscans* from 1993–2014 estimated from the base biomass dynamic model. Dashed red line denotes BMSY for *E. coruscans*.

An index of population abundance, such as standardised CPUE, is used to measure shifts in population size over time. Factors influencing catch rates (nominal CPUE) are considered when deriving estimates of standardised CPUE such as shifts in fishing behaviour and effort over time which can influence catch rates from year-to-year and can mask changes in population size.

We modelled trends in standardised CPUE of *E. coruscans*, calculated using catch weight (kg) per hook hour, over time under different scenarios with generalized additive models (GAMs) to look at the influence and impact of different factors. The three scenarios considered included:

- **Base model** – factors considered included: year, month, depth fished, vessel, region, species composition.
- **Active vessels** – base model for vessels that completed >15 trips per year.
- **Core area** – base model for grid cells (0.5°) that recorded >1 fishing trip every 5 years.

Nominal CPUE was available for 1993 to 1998 and 2005 to 2014 but unavailable for 1999 to 2004, as catch and effort were reported in other units during these years. The influence of vessel and spatial expansion of effort were investigated by running separate BDM scenarios, using the R package bdm (Edwards, 2015). The estimates of standardised CPUE varied slightly among the three scenarios (**Fig. 3**). The estimates of CPUE were greater from 1994-1998 when only active vessels were included. The difference was marginal between the base scenario and core area only standardisation. Estimates of standardised CPUE were very similar for all three scenarios from 2005–2014, which is likely reflective of the consistency in fishing operations during this period..

Standardised CPUE was highest in the early years (1993-1998) for all scenarios, though the error in CPUE estimates was also greatest due to limited data during this period (**Fig. 3**). CPUE decreased by ~60% between 1998 and 2005 suggesting a decline in population size of *E. coruscans*. CPUE remained relatively constant (0.3–0.5) from 2005-2014 despite variation in total effort. A slight increase in CPUE from 2008 to 2014 suggests a decline in effort may have allowed a small recovery in abundance.

Results

The biomass dynamic model for the *E. coruscans* population estimated that the current biomass (2014), in all three scenarios, has been depleted to between 26-36% of 1993 levels (**Table 1**). MSY for *E. coruscans* was calculated to be 74–87 tonnes across the three scenarios. Biomass dropped below B_{MSY} sometime between 1998 and 2005 and has remained beneath this level since (**Fig. 4**). Catches in 2000, 2001 and 2005 to 2007 were in excess of MSY estimates. From 2005 to 2014 there was a general increasing trend in population levels, with predicted biomass increasing from 25 to 30% of 1993 levels. However, population levels in 2014 remained below those required to achieve MSY and current harvest rates are lower than the harvest rate at MSY. Using the convention for reporting stock status where a limit reference point has not been defined, the biomass dynamic models suggest that the stock is overfished ($B_{2014}<B_{MSY}$) but not currently subject to overfishing ($F_{2014}<F_{MSY}$).

Table 1: Biomass dynamic model outputs for all three scenarios of the Tongan Deepwater Line Fishery.

Scenario	MSY (t)	Biomass at MSY (t)	Harvest rate at MSY	Current (2014) biomass (t)	Current (2014) depletion	Current (2014) harvest rate
Base	80.3	2436.2	0.032	1438.8	0.29	0.021
Active vessels	74	2151.1	0.034	1518.8	0.36	0.019
Core area	86.6	2905.8	0.030	1527.1	0.26	0.029

Limitations

Inconsistent data collection schemes have compromised the performance of the biomass dynamic model for *E. coruscans*, due to gaps in the nominal and standardised CPUE series. Furthermore, the biomass dynamic models presented here assume that standardised CPUE is proportional to stock abundance, an assumption which is frequently violated in practise and requires fishery-independent abundance indices to test. Finally, the fishery developed in the 1980s, but data reporting of catch weight commenced only in 1993. Consequently, an unknown quantity of the stock biomass was removed from the stock prior to 1993, but not included in the BDM. As such there is uncertainty in estimates of *E. coruscans* stock status derived from this method in isolation.

2. Length-based indicators

Monitoring program

» Fish length data collection program

» Estimate of length at maturity

This technique uses simple length-based population indicators to inform management of changes in stock structure over time (Froese 2004). This technique requires a representative sample of the length-frequency distribution of species captured within the fishery and estimates of age at maturity. It is useful for data-poor fisheries where traditional stock assessment techniques are not viable. This technique monitors three indicators within the catch which act as indicators for stock health (**Fig. 5**).

1. Percentage of mature fish
2. Percentage of fish that are within the optimum length (L_{opt})
3. Percentage of fish that are mega-spawners

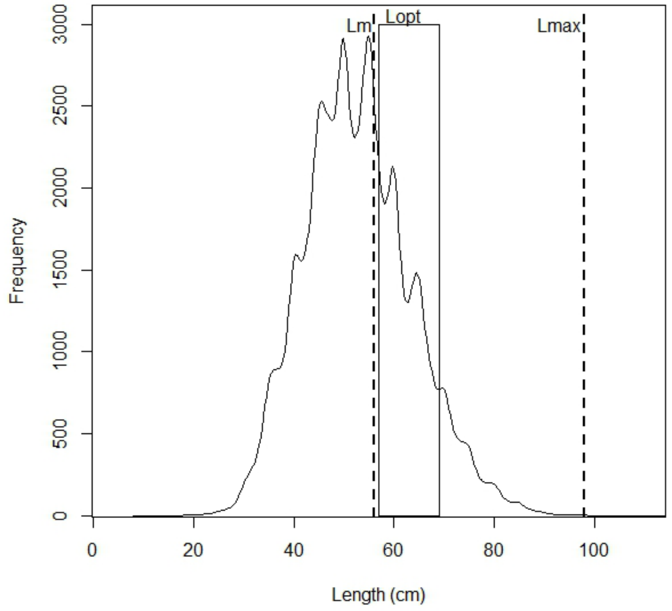


Figure 5: Length-frequency distribution plot outlining the position of length-based indicators defined by Froese (2004) in a theoretical population.

These three measures provide an indication of stock structure and warn managers if the spawning biomass is becoming depleted to levels that may be of concern. The aim is to maximize the proportion of mature fish captured within the fishery, allowing each individual to spawn and contribute to the population prior to harvest. Lopt represents the length range where potential yield is highest, i.e the mean weight of fish in this length range multiplied by the number of fish in this length range provides maximum yield. Mega-spawners refers to large fish within the population (L_{opt} + 10%) that are assumed to provide a disproportionately large number of recruits to the population through greater egg production and survival, which has been observed for many species.

Using length-frequency data collected from 1993–2014, we investigated length-based indicators for *E. coruscans* and *P. filamentosus*. Prior to 1993, only mean length data were available.

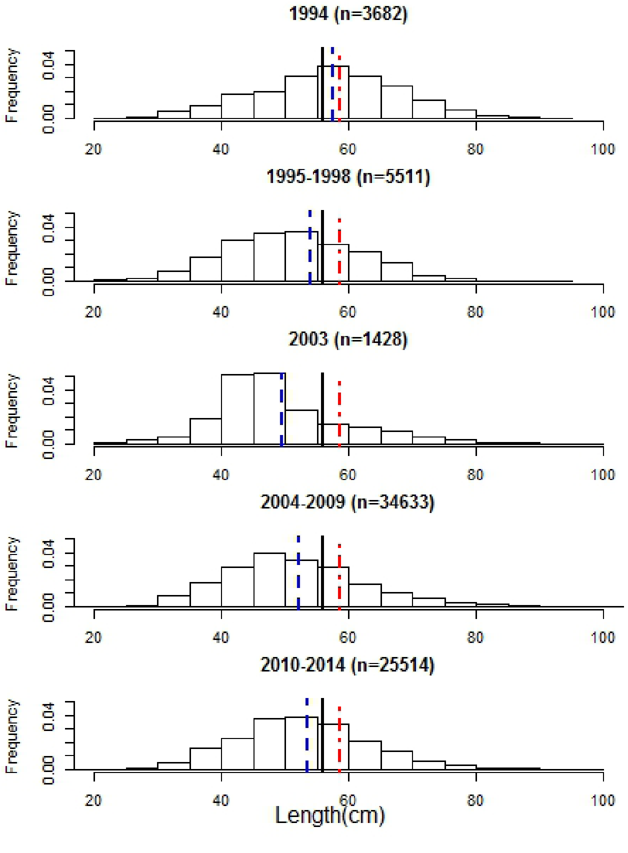


Figure 6: Length-frequency distribution of *E. coruscans* across five time periods showing shifts in population structure. Length at maturity (black), mean length recorded from 1987–1991 (red) and mean length recorded for the time period (blue) are represented as vertical lines.

Etelis coruscans

Length at maturity: 56 cm FL

Length optimum: 57-69 cm FL

Mega-spawners: >69 cm FL

The length-frequency distribution of *E. coruscans* catch is characterised by a low proportion of mature individuals (20–60%) (**Fig. 6**). This reflects the small size at which *E. coruscans* recruits to the fishery (~20 cm FL). The mean length of *E. coruscans* captured in early years of the fishery (1987–1991) was 58.7cm. From

1993–1998, the proportion of mature individuals and mega-spawners declined by nearly 50%, suggesting that the spawning population decreased (**Fig. 7**). Length indicators suggest the population was at its most depleted in 2003, with only 22% of individuals captured reaching maturity and a mean overall length of 49.5cm. From 2004 onwards, the stock has shown signs of recovery with the mean length of fish captured reaching 53.6cm from 2010–2014. The percentage of mature individuals harvested has increased from 22% to 38% from 2003–2014.

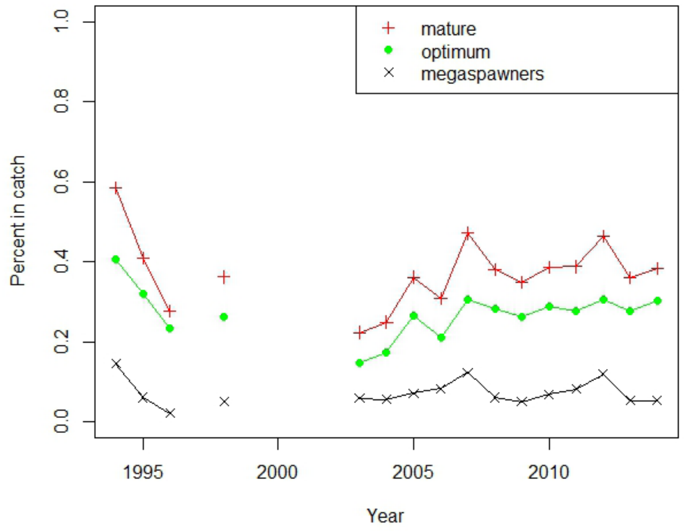


Figure 7: Length-based population indicators for *E. coruscans* from 1994–2014. No data for 1997 or from 1999–2002.

The decline in mean length and proportion of mature fish coincided with the period of peak fishing effort and harvest, suggesting that fishing reduced the size of the spawning population. The slight increase in mean length and proportion of mature *E. coruscans* from 2003 suggest that recent harvest rates (2004 onwards) may have allowed an increasing proportion of the stock to reach maturity. However, no recovery in mega-spawners has occurred, representing <10% of harvest.

Pristipomoides filamentosus

Length at maturity: 41 cm FL

Length optimum: 47–59 cm FL

Mega-spawners: >59 cm FL

The proportion of mature *P. filamentosus* has remained relatively high (~80%) for the entire period in which data is available (**Fig. 9**). This is most likely due to the small length at maturity of *P. filamentosus* (41 cm FL) relative to *E. coruscans*. Also, juvenile *P. filamentosus* occupy a different habitat niche than adults and, therefore, may not recruit to fishing grounds until greater lengths.

The mean length and mode of *P. filamentosus* from 1994–2014 has ranged from ~45–50cm, remaining consistently above the length at maturity (**Fig. 8**). However, the mean and modal length have remained below those recorded in 1987–1991 of 52.8 cm, suggesting that fishing may have decreased the proportion of larger individuals in the population. A decline in the number of mega-spawners and the mean and modal length across time suggests that the length structure of *P. filamentosus* may have been altered by fishing. However, *P. filamentosus* is afforded some protection from the effects of fishing due to the smaller length at maturity relative to *E. coruscans*.

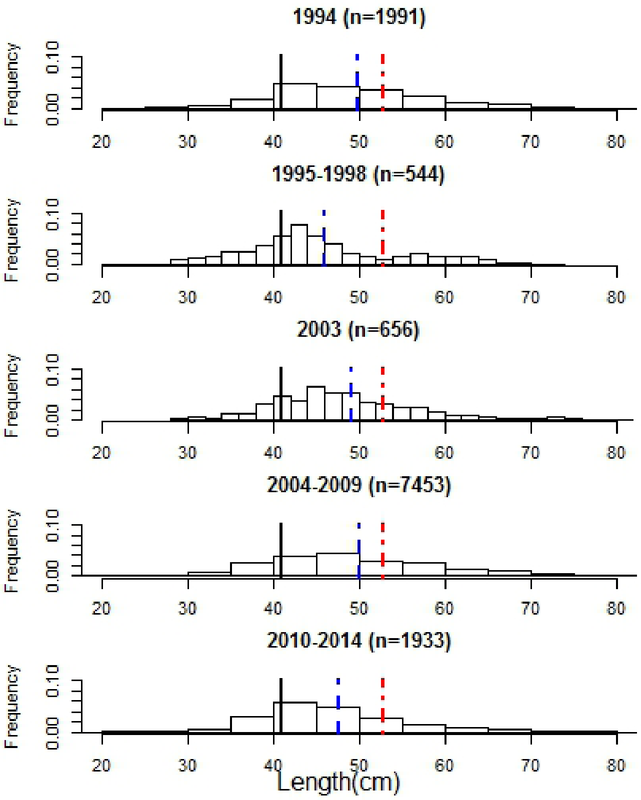


Figure 8: Length-frequency distribution of *P. filamentosus* across five time periods showing shifts in population structure. Length at maturity (black), mean length recorded (red) from 1987–1991 and mean length recorded for the time period (blue) are represented as vertical lines.

Limitations

Absence of length-frequency data at the commencement of the deepwater snapper fishery limits our ability to determine the overall impacts of the fishery on species because we cannot establish initial length distributions prior to exploitation. Data collected from 1987–1991 (MRAG, 1994) suggests that the population structure of both *E. coruscans* and *P. filamentosus* has shifted. Missing and inconsistent collection of length-frequency data reduces the strength and reliability of trends observed. Despite this, clear trends in the population of both *E. coruscans* and *P. filamentosus* over time are present and can help inform management decisions.

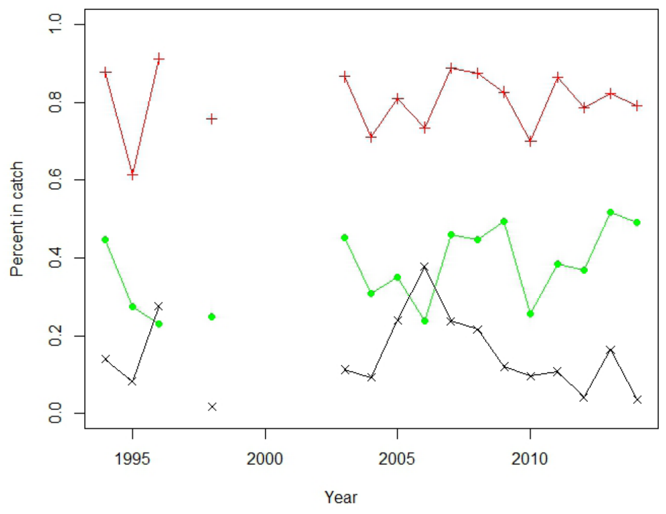


Figure 9: Length-based population indicators for *P. filamentosus* from 1994–2014. No data in 1997 or from 1999-2002.

3. Catch-curve analysis

Monitoring program

- Otolith collection scheme
- Estimate of natural mortality

Catch-curve analysis is used to gain an estimate of mortality derived from the age structure of fish populations. Shifts in the age structure of populations over time provide management with an indication of fishing pressure. Catch curves require a representative age distribution, which is usually obtained from otoliths.

Catch curves provide an estimate of total mortality (Z), which consists of two components: fishing mortality (F) and natural mortality (M), such that $Z = M + F$. A regression-based catch-curve approach was used to gain an estimate of total mortality (Millar, 2015). For *E. coruscans*, sexes were analysed separately due to divergent life histories, with females having greater longevity. Otoliths from *E. coruscans* were collected from within Tongan waters in 2012 (n = 489) and 2013 (n = 478), allowing two estimates of mortality to be calculated. Natural mortality was estimated from the equation: $M = e^{(1.46 - 1.01 * ln(max\ age))}$ which is derived from maximum age recorded for a species, also estimated separately for both sexes (Hoenig, 1983). Estimates of maximum age for male (38 years) and female (34 years) *E. coruscans* were obtained from samples collected from unexploited populations in the Pacific Ocean (A. Williams, unpublished data). This led to natural mortality estimates of 0.109 for females and 0.122 for males.

Results

For 2012, estimates of fishing mortality were 0.021 for females and 0.016 for males (**Table 2**). Fishing mortality for both sexes was less than half of the estimate of natural mortality. In 2013, fishing mortality increased, with an estimate of 0.058 for females and 0.025 for males. Assuming representative sampling of the catch, a decline in *E. coruscans* status is present from 2012 to 2013. However, with only two years of data, it is difficult to know if this is driven by natural variability, shifts in harvest rates, or non-representative collections of otoliths.

Limitations

Catch curve analysis is based on numerous assumptions about the population and samples collected. It assumes that both recruitment and mortality are constant from year to year and across all age classes. This assumption is likely to be violated, as there is inherent variability in recruitment and mortality rates for most fish species. However, this technique provides an indicator that can be used to look at shifts in populations over time in response to fishing, and it will become more informative as additional samples are collected in future years.

Management options

Trigger or reference points can be assigned based on the outcomes of each assessment technique to initiate management decisions. As seen in **Table 3**, examples of possible trigger points are provided for each assessment technique. Outcomes from the BDM and length-based indicators showed similar results, and values of fishing mortality were consistent between the BDM and catch-curve analysis. This provides confidence in the outcomes of each assessment technique. Harvest and effort levels have reduced recently, allowing stock declines to pause. It would be prudent to ensure that harvest and effort levels are maintained at recent levels or further reduced to allow stocks to recover to higher levels which are consistent with the management objectives for the fishery. For example, based on the outcomes of the length-based indicators, maintaining or decreasing effort or harvest rates may allow the *E. coruscans* population to continue recovering towards the target of B_{MSY}. Continued monitoring of deepwater fisheries into the future will allow fisheries to update and adjust these decision rules as further information is gathered.

Table 2: Estimates of total (Z) and fishing (F) mortality for sexed *E. coruscans* in 2012–2013. Estimate of natural mortality (Hoenig 1983) was 0.109 for females and 0.122 for males.

	Sample Size	Total Mortality (Z)	Fishing Mortality (F)
Male (2012)	215	0.14	0.016
Female (2012)	274	0.13	0.021
Male (2013)	196	0.15	0.025
Female (2013)	282	0.17	0.058

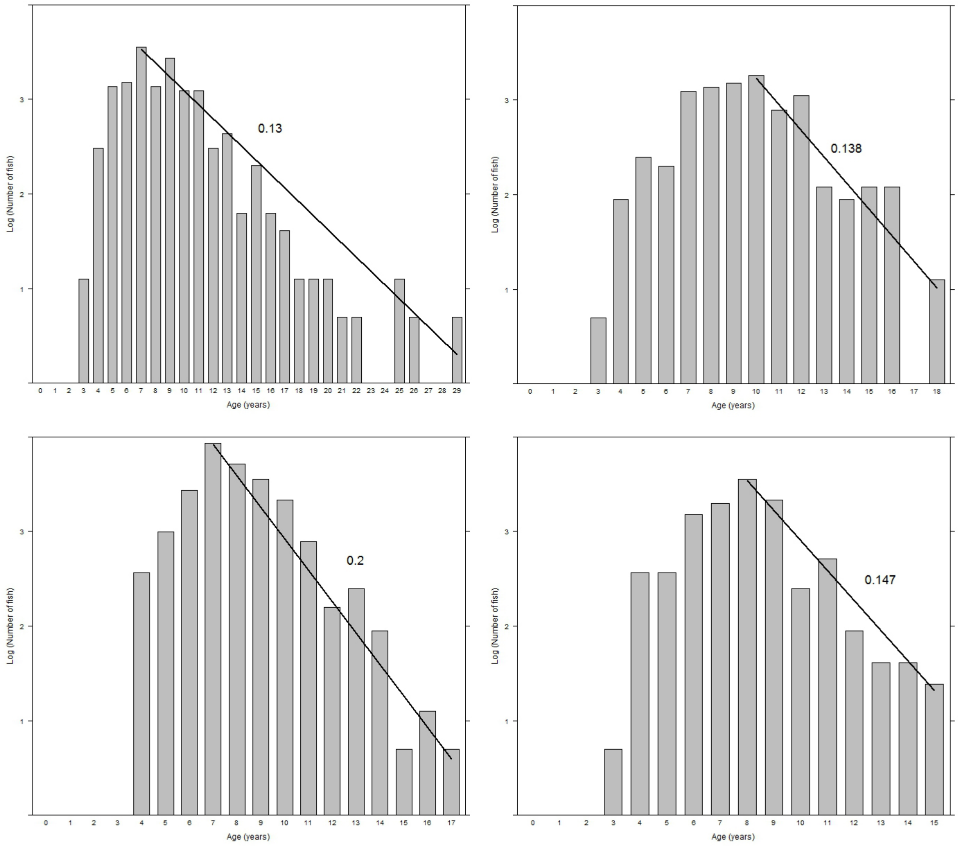


Figure 10: Catch curve analysis of sexed *E. coruscans* across 2012–2013. A) Male 2012, B) Female 2012, C) Male 2012, D) Female 2013.

Outcomes

The capacity for PICTs to autonomously manage fisheries resources is essential to ensure sustainability and their continuing benefit to these nations. This fact-sheet has outlined three practical assessment techniques and applicable decision rules that will facilitate the formation and implementation of formal harvest strategies based on country-specific management objectives.

For Tonga, it is recommended that current data collection programs are maintained, including the collection of detailed catch and effort, length and sex data from the catch, and the sampling and processing of otoliths to estimate age. Length, sex and age-based data can be collected simultaneously from the catch, streamlining data collection for alternate assessment techniques. Key indicator species should be identified to allow concentration of resources, improving sample sizes and data quality. Due to high resource demand of biomass dynamic models, length and age-based assessment techniques are a more practical option for resource-limited fisheries such as those for deep-water snapper in the Pacific. These indicators can be used to monitor the fishery from year-to-year with further data analyses or assessment required only if further funding is allocated or a reference point is triggered. This will allow resource-limited fisheries, such as Tonga's deepwater snapper fishery, to be largely autonomous of external funding, improving the adaptive capacity of management.

Table 3: Example of decision rule table based on outcomes of each assessment technique.

Assessment outcome	Decision rule
1. Harvest < $\text{Harvest}_{\text{target}}$ 2. %mature > $\text{\%mature}_{\text{target}}$ 3. $F < F_{\text{target}}$	Maintain or increase quota/effort.
1. Harvest = $\text{Harvest}_{\text{target}}$ 2. %mature = $\text{\%mature}_{\text{target}}$ 3. $F = F_{\text{target}}$	Quota/effort should remain constant. Potential for increased data collection/analysis.
1. $\text{Harvest}_{\text{target}}$ < Harvest < $\text{Harvest}_{\text{limit}}$ 2. $\text{\%mature}_{\text{target}}$ > %mature > $\text{\%mature}_{\text{limit}}$ 3. $F_{\text{target}} < F < F_{\text{limit}}$	Decrease quota/effort eg: 0-50%.
1. Harvest > $\text{Harvest}_{\text{limit}}$ 2. %mature < $\text{\%mature}_{\text{limit}}$ 3. $F > F_{\text{limit}}$	Decrease quota/effort substantially eg: 50-100%.

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