Demographic assessment of exploited coastal finfish species of Tongatapu, Tonga

Pacific Community
Communauté du Pacifique

Demographic assessment of exploited coastal finfish species of Tongatapu, Tonga

by

Brad Moore[1] and Siola'a Malimali[2]

[1]Coastal Fisheries Programme, Pacific Community (SPC)
[2]Fisheries Department, Tonga Ministry of Agriculture, Food, Forests and Fisheries

Noumea, New Caledonia, 2016

Original text: English

Pacific Community Cataloguing-in-publication data

Moore, Bradley

Demographic assessment of exploited coastal finfish species of Tongatapu, Tonga / by Brad Moore and Siolaá Malimali

1. Fishes — Tonga.

2. Fisheries — Tonga.

3. Fishery resources — Tonga.

I. Moore, Bradley II. Malimali, Siolaá III. Title IV. Pacific Community

338. 3727099612 AACR2

ISBN: 978-982-00-1012-3

Prepared for publication and printed on 100% recycled paper at the Pacific Community
BP D5, 98848 Noumea Cedex, New Caledonia.

Contents

Acknowledgements

Tonga's Fisheries Department and the Pacific Community (SPC) acknowledge with gratitude the financial support of the European Union for funding the survey work in Tonga and processing of otolith material under the Scientific Support for the management of Coastal and Oceanic Fisheries in the Pacific Islands region (SciCOFish) project.

This assessment was made possible by the assistance and contribution of many people and agencies. We gratefully acknowledge the collaboration of the Fisheries Department staff who participated in the training and assisted with sampling in Tongatapu, in particular (in alphabetical order) Tracy 'Aisea, Malakai Faletau, Viliami Fatongiatau, Ioane Finau, Siaosi Fonua, Mafi Havea, Sitaleki Mafi, Sione Mailau, Tonga Tu'iano, Sione Uasike, Siua Vaiangina and Siaosi Vi. We also thank the Director of Fisheries, Nunia Mone, for her support for the assessment. Kyne Krusic-Golub and Simon Robertson from Fish Ageing Services (http://www.fishageingservices.com/) assisted with the development of ageing protocols, otolith sectioning, and estimation of fish ages. Ian Bertram (SPC Coastal Fisheries Programme) provided constructive comments on a draft version of the report.

Summary

Coastal finfish populations have long provided an important source of food and economic activity for the people of Tongatapu. However, recent surveys suggest that the coastal finfish resources of Tongatapu are moderately to seriously overexploited, with significant declines in abundance observed for some species and decreases in size for others. In light of these observations, Tonga's Fisheries Department requested assistance from the Pacific Community's Coastal Fisheries Programme with training in biological sampling and a preliminary assessment of the demography of selected coastal finfish species at Tongatapu, Tonga.

Training and data collection took place in July 2014. Three types of assessments were conducted: an assessment of otolith readability for those species with untested otoliths, an assessment of sex-specific length frequencies and length-weight relationships of selected species with adequate sample sizes; and an assessment of age-based demography, including age structures, growth rates, age at maturity, and mortality estimates for selected species with known otolith readability. Assessments of otolith readability were conducted on three species: largescale mullet (*Liza macrolepis*), sea mullet (*Mugil cephalus*) and forktail rabbitfish (*Siganus argenteus*). Otoliths of the two mullet species could be processed using standard techniques and were relatively easy to interpret, suggesting otolith-based approaches are a viable method of assessing the status of these species. Given their small size and fragile nature, otoliths of *Siganus argenteus* required processing using hand-ground transverse sectioning approaches. Once sectioned, otoliths were relatively easy to interpret, again suggesting this species could potentially be assessed using otolith-based approaches in future assessments (albeit at greater cost and effort to section otoliths).

Detailed age-based demographic parameters were estimated for five species: striated surgeonfish (*Ctenochaetus striatus*), orangestripe emperor (*Lethrinus obsoletus*), blacktail snapper (*Lutjanus fulvus*), orangespine unicornfish (*Naso lituratus*) and bluespine unicornfish (*Naso unicornis*). These species were chosen for this preliminary assessment because they constitute an important component of the coastal finfish catch at Tongatapu, and sufficient sample sizes were able to be collected during the time of survey.

Fifty-six *Ctenochaetus striatus* were sampled from the spearfishing catch of Tongatapu during the training. Lengths of these individuals ranged from 14.2 – 24.0 cm fork length (*FL*), with an average length of 18.3±0.2 cm *FL*. Estimated ages ranged from 2 – 40 years, with a modal age of 7 years. Fishing mortality was calculated to be 0.02 yr^{-1}; below the maximum optimal fishing mortality rate of 0.05 yr^{-1}, suggesting this species is not presently overexploited.

Sixty-three individuals of the protogynous hermaphrodite *Lethrinus obsoletus* were sampled during the training. Lengths ranged from 13.1 – 28.0 cm *FL*, with an average length of 21.9 cm *FL*, and a modal length class of 24.0 – 24.9 cm *FL*. Estimated ages for *L. obsoletus* at Tongatapu ranged from 0 – 16 years, with a modal age of 3 years. Fish captured by fish fences were significantly smaller and younger than those caught by spearfishing. The length and age at which 50% of females became mature was estimated to be approximately 22.3 cm *FL* and 2.9 years. Total mortality was estimated to be 0.19 yr^{-1}. Natural mortality was estimated to be 0.20 yr^{-1}, suggesting a poor fit to the mortality calculations. As such, no estimates of fishing mortality were established for this species.

Twenty-four *Lutjanus fulvus* were sampled during the training. Lengths ranged from 17.9 – 28.4 cm *FL*, with an average length of 23.4±0.5 cm *FL*. Estimated ages ranged from 2 – 25 years, with a modal age of 2 years. Due to low sample sizes, no estimates of mortality or maturity were established for this species.

One hundred and ten *Naso lituratus* were sampled during the training. Lengths ranged from 16.1 – 26.5 cm *FL*, with an average length of 20.9±0.2 cm *FL*. Estimated ages for *N. lituratus* ranged from 1 – 4 years, with a modal age of 2 years. The maximum observed age was considerably lower than that observed elsewhere in the region. The length and age at which 50% of females became mature was approximately 18.6 cm *FL* and 0.9 years of age, while 50% of males became mature at 20.3 cm *FL* and 1.4 years. Fishing mortality for *N. lituratus* was estimated to be 0.99 yr^{-1}, more than six times the maximum optimal fishing mortality rate of 0.15 yr^{-1}.

One hundred *Naso unicornis* were sampled during the training. Lengths ranged from 14.1 – 51.5 cm *FL*, with an average length of 30.5±0.8 cm *FL*. Ages ranged from 0 – 6 years, with a modal age of 2 years. As with *N. lituratus*, the maximum observed age for *N. unicornis* was considerably lower compared with elsewhere in the region. The length and age at which 50% of females were mature was approximately 28.1 cm *FL* and 2.2 years, while 50% of males became mature at 30.8 cm *FL* and 2.6 years of age. Fishing mortality for *N. unicornis* was estimated to be 0.67 yr^{-1}; almost 10 times the maximum optimal fishing mortality reference point of 0.07 yr^{-1}.

The high rates of fishing mortality estimated for *N. lituratus* and *N. unicornis* suggest that fishing effort on these two species, and thus in the night-time spear fishery, is well above a sustainable level and needs to be reduced. Without urgent and decisive management attention, the current unsustainable rate of fishing is likely to result in diminished populations and further reductions in size of remaining individuals of these species, with significant social and ecological consequences. Potential options to reduce the amount of total fishing effort on the inshore finfish resources of Tongatapu are discussed, including:

1. Increasing the cover (including the number and size) of marine managed areas where a proportion of the fished population is protected from fishing;
2. Enforcing size limits and/or slots to reduce fishing pressure on the smallest and/or largest individuals;
3. Reducing the number of days a vessel can fish;
4. Reducing the number of fishers per vessel;
5. Imposing a nightly catch or species bag limits;
6. Improving fishers' and the general public's education and awareness of reef fish biology, including lengths and ages at maturity, maximum ages and life cycles, and of the status of coastal finfish populations of Tongatapu;
7. Moving fishing pressure away from reef resources and towards small pelagic fish;
8. Undertaking greater enforcement of existing fisheries management regulations;
9. Banning night-time spearfishing.

In addition, we recommend that monitoring, including the collection of catch and effort data and biological samples for demographic assessments, continue in order to evaluate the success of any management interventions taken, as well as to monitor the status and trends in productivity of Tongatapu's coastal fisheries.

1. Introduction

Background

The Kingdom of Tonga (hereafter referred to as Tonga) is a Polynesian archipelago consisting of 36 inhabited and 134 uninhabited islands that are scattered among three main island groups: Tongatapu, Ha'apai and Vava'u. Tonga has an estimated land area of 749 km^2 and an exclusive economic zone of 676,401 km^2 (Bell et al. 2011). Its population in 2011 was 103,252, with approximately 38% of the population aged between 0 and 14 years (Tonga Department of Statistics 2015). Around 70% of the population lives on Tongatapu (Tonga Department of Statistics 2015).

Fishing has long been an important commercial and subsistence activity throughout Tonga, to which Tongatapu is no exception. The inshore fishing grounds of Tongatapu cover an estimated 947 km^2, of which reefs and mangroves comprise 11.2% and 0.36%, respectively (Lovell and Palaki 2003). Accordingly, coastal fisheries provide an important source of income and protein for the people of Tongatapu. Recent surveys under the Pacific Regional Oceanic and Coastal Fisheries Development Programme coordinated by the Pacific Community (SPC) revealed that at Ha'atafu, on the western side of Tongatapu, fisheries provide about 28% of all households with their primary source of income and another 5% of all households with secondary income (Friedman et al. 2009). Per capita consumption of fresh fish was found to be approximately 92 kg per person per year, almost three times higher than the regional average of 35 kg per person per year, while invertebrate consumption was similarly high with approximately 21 kg consumed person per year (Friedman et al. 2009).

On Tongatapu, as is common among many Pacific Islands, almost all potential food fish are harvested and eaten by locals, with the only exceptions being certain species suspected of being ciguatoxic. A variety of fishing methods are used to target fish on the coral reefs, lagoons and mangrove areas of Tongatapu, including netting, handlining, fish fences (traps) and trolling, although night-time spearfishing is the dominant fishing method (B. Moore, pers. obs.). In particular, the practice of *taufale* is gaining popularity, especially among older fishers. This term comes from the name of the traditional broom used in Tonga and describes a process whereby night spearfishers snorkel a length of a shallow reef flat area and harvest all edible fishes they come across (i.e. 'sweeping' the reef). This method is overly efficient as it targets individuals sleeping on the reef when they are easily visible and accessible to spearfishers.

Recent surveys suggest the coastal finfish resources of Tongatapu are moderately to seriously overexploited (Malm 2001; Friedman et al. 2009). Significant declines in abundance have been observed for some species while others have decreased in size (Malm 2001; Friedman et al. 2009). For example, sea mullet, *Mugil cephalus*, formed about 70% of the commercial mullet landings while mullet accounted for about 40% of all marketed fish in the 1970s, after which their numbers declined to almost the point of local extinction (Wilkinson 1977; Bell et al. 1994). This trend in declining abundance has been attributed by some to the introduction of overly-efficient fishing methods, such as night-time spearfishing or fish fences that catch fish as they migrate to their spawning grounds (Langi et al. 1987, 1988).

Fisheries management in Tonga

Management systems for finfish fisheries in Tonga are a mix of input and output controls, and include gear restrictions, spatial and temporal closures, and export restrictions. For example, fishing on scuba or underwater breathing apparatus (UBA) is prohibited, as is using drag nets or beach seines within 200 m of a fish fence. Only licenced operators can erect or use fish fences, and restrictions on the size and locations of fish fences are in force. A minimum legal stretched mesh size of 38 mm is in place for drag nets or beach seines, while a minimum legal stretched mesh size of 12 mm is in place for cast nets. A closed season on the capture and sale of mullet (all species) occurs from 1 June to 31 July (The Fisheries [Conservation and Management] Regulations 1994). Exports of live fish are prohibited without written authorisation. In addition, there are three Special Management Areas (SMAs) in Tongatapu (at 'Atata, 'Eueiki and Fafa). Beyond these restrictions, coastal fisheries of Tongatapu are largely 'open access', with no limits on the number of people or boats fishing, days they can fish, or amount of fish that can be caught.

Biological sampling as a tool for fisheries assessment and management

Understanding the life history of exploited species is critical to successful fisheries management. Demographic parameters such as age structures, growth rates, maturity profiles and mortality rates provide key information on the status of exploited species and are integral to the development and evaluation of future management strategies (Haddon 2001). Without such data, it is very difficult to assess the current status of a population, predict the response of a species to exploitation, or assess the effectiveness of fishery controls.

Until recently, age-based studies on the life history of tropical fish species were rare, largely due to the perceptions that tropical fish do not deposit reliable annual increments in their otoliths (Choat et al. 2009). However, numerous recent studies across a wide range of taxa have demonstrated that otoliths from tropical fish provide reliable age estimates (Trip et al. 2008; Taylor et al. 2014).

Objectives of this study

In March 2014, Tonga's Fisheries Department requested assistance from the Coastal Fisheries Programme of the Pacific Community (SPC) with an assessment of the demography of key coastal finfish species. The purpose was to train fisheries staff in biological sampling, assess the current state of finfish resources and allow for a reference point for future demographic comparisons. Training was conducted in July 2014 and involved 13 Fisheries Department staff. Finfish samples used in this assessment were sampled from coastal fishers during creel surveys conducted by Fisheries Department staff under SPC's guidance (see Methods section).

In this report we provide the results of three types of assessments conducted on the finfish species surveyed:

1. An assessment on the readability of otoliths of species with unknown readability to guide future assessments;
2. An assessment of sex-specific length frequencies and length-weight relationships of selected species with adequate sample sizes; and
3. Detailed age-based demographic assessment, including an examination of age structures, age and growth parameters, length and ages at maturity, and mortality rates, of selected species with proven otolith readability and adequate sample sizes.

Recommendations for management, monitoring and future research are also provided.

2. Methods

Sample collection

Finfish samples used in this assessment were collected from commercial fishers during creel survey operations or from fish markets where the date, location and method of collection was known. All samples were collected between 3 and 15 July 2014 inclusive.

Collected fish were taken to the Fisheries Department laboratory for processing. Fork length (*FL*) and total length (*TL*) were measured to the nearest millimetre, and whole wet weight (*W*) measured to the nearest 1 g for each fish collected, unless damaged. Sex and maturity stage were determined from a macroscopic examination of the gonads. Gonads were removed, trimmed of excess tissue, and weighed to the nearest 0.001 g. Sagittal otoliths (hereafter referred to as otoliths) were removed, cleaned, dried and stored in plastic vials until processing in the laboratory.

Otolith processing

A single otolith from each fish was weighed to the nearest 0.001 g using an electronic balance, unless broken. Otoliths from *Ctenochaetus striatus*, *Lethrinus obsoletus*, *Liza macrolepis*, *Lutjanus fulvus*, *Mugil cephalus*, *Naso lituratus* and *Naso unicornis* were processed using standard sectioning protocols. Here, a single otolith from each individual was embedded in resin and sectioned on the transverse axis using a slow-speed diamond edge saw. Sections were approximately 300 µm thick, and care was taken to ensure the primordium of the otolith was included in the sections. Sections were cleaned, dried and mounted onto clear glass microscope slides under glass coverslips using resin.

Due to their small size and fragile nature, otoliths from *Siganus argenteus* were prepared using the single ground transverse sectioning method described in Robertson and Krusic-Golub (2015). Briefly, a single otolith from each fish was fixed on the edge of a slide using thermoplastic mounting media (CrystalBond), with the anterior of the otolith hanging over the edge of the slide, and the primordium just inside the slide's edge. The otolith was then ground down to the edge of the slide using 400 and 800 grit wet and dry paper. The slide was then reheated and the otolith removed and placed on a separate slide with CrystalBond, with the ground surface facing down. Once cooled, the otolith was ground horizontally to the grinding surface using varying grades (400, 800, 1200 and 1500 grit) of wet and dry paper and polished with lapping film.

Mounted otolith sections from all species were examined under a stereo microscope with reflected light. Opaque increments observed in the otolith were assumed to be annuli for all species examined. Supportive evidence for annual periodicity in opaque increment formation in otoliths has been demonstrated in the majority of cases for tropical reef fish (e.g. Choat and Axe 1996; Newman et al. 1996; Pilling et al. 2000; Shimose and Nanami 2014). The annuli count was accepted as the final age of the individual, with no adjustment made for birth date or date of capture.

Assessments of otolith readability

Assessments of otolith readability were conducted for those species where the readability of otolith sections was untested in the region, namely for *Liza macrolepis*, *Mugil cephalus* and *Siganus argenteus*. Otolith readability was assessed qualitatively, via observations of whole and sectioned otoliths, and quantitatively, by assigning a readability score which rates the readability of each otolith from 1 (poor) to 10 (clear) (Robertson and Krusic-Golub 2015).

Demographic analyses

Detailed demographic analyses were limited to those species with known otolith readability and where sufficient sample sizes were available (Table 1). Length and age frequency distributions were constructed to examine population structures of each species. Chi-squared tests were used to compare age frequency distributions among sexes using R (R Core Team 2013). The relationship between length and weight was described using a power function of the form:

$$W = a \times FL^b$$

To examine growth patterns, the von Bertalanffy growth function (VBGF) was fitted by nonlinear least-squares regression of length (*FL* or *TL*) on age. The form of the VBGF used to model length-at-age data was as follows:

$$L_t = L_\infty[1 - e^{-K(t-t_0)}]$$

where L_t is the length of fish at age t, L_∞ is the hypothetical asymptotic length, K is the growth coefficient or rate at which L_∞ is approached, and t_0 is the hypothetical age at which fish would have a length of zero. Due to a lack of smaller, younger fish in the samples, t_0 was constrained to zero. A single VBGF was fitted for hermaphroditic species (*L. obsoletus*), while sex-specific VBGFs were initially fitted for gonochoristic species (*C. striatus*, *L. fulvus*, *N. lituratus* and *N. unicornis*). Likelihood ratio tests were used to test for differences in VBGF parameters among sexes using MS Excel. Where no differences were observed, VBGF curves were fitted for individuals of both sexes combined.

Age-based catch curves (Ricker 1975) were used to estimate the instantaneous rate of total mortality (Z) for each species with samples sizes ≥50. Catch curves were generated by fitting a linear regression to the natural log-transformed number of fish in each age class against fish age. The slope of this regression is an estimate of the rate of annual mortality. Regressions were fitted from the first modal age class, presumed to be the first age class fully selected by the sampling gear, to the oldest age class that was preceded by no more than two consecutive zero frequencies. Instantaneous natural mortality rates (M) were derived using the general regression equation of Hoenig (1983) for fish:

$$\ln(M) = 1.46 - 1.01 \times \ln t_{max}$$

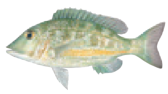
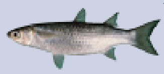
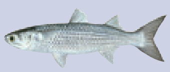
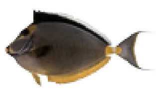
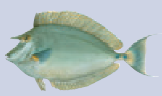
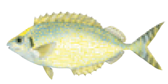
where t_{max} is the maximum known age, in years. Estimates of fishing mortality (F) were derived by subtraction ($F = Z - M$). The harvest strategy of $F_{opt} = 0.5M$ (Walters 2000) was adopted in this study as the optimum fishing mortality rate for sustainable exploitation. This reference point seeks to ensure adequate egg production and, therefore, the maintenance of recruitment, and is used routinely as a mortality reference point for tropical, data poor fisheries (Walters 2000; Newman and Dunk 2002).

Length and age at 50% maturity was determined for *L. obsoletus*, *N. lituratus*, *N. unicornis* and *S. argenteus* (length only) by logistic regression analysis, using the following equation:

$$Pm = 1/[1 + \exp(-\ln(19)\,(m - m_{50})/(m_{95} - m_{50}))]$$

where Pm = the proportion of mature fish in each age or 5 mm FL class m and m_{50} and m_{95} are the lengths or ages at which 50% and 95% of the population is mature, respectively. The data (immature or mature) were randomly re-sampled and analysed using Solver in MS Excel to create 50 sets of bootstrap estimates for the parameters of the logistic equation and estimates of the probability of maturity within the recorded lengths and ages. The point estimates for each parameter and of each probability of maturity were taken as the medians of the bootstrap estimates.

Table 1: Finfish species assessed and parameters investigated in this study.

Species image	Local name	Common English name	Scientific name	Parameters investigated
	pone'uli	striated surgeonfish	*Ctenochaetus striatus*	Length and age frequencies, VBGF parameters, mortality rates
	tanutanu	orangestripe emperor	*Lethrinus obsoletus*	Length and age frequencies, VBGF parameters, mortality rates
 [1]	'unomoa	largescale mullet	*Liza macrolepis*	Otolith readability
	tanga'u	blacktail snapper	*Lutjanus fulvus*	Length and age frequencies, VBGF parameters
	kanahe	sea mullet	*Mugil cephalus*	Otolith readability
 [1]	'umelei	orangespine surgeonfish	*Naso lituratus*	Length and age frequencies, VBGF parameters, mortality rates, length and age at maturity
	'umekaki	bluespine surgeonfish	*Naso unicornis*	Length and age frequencies, VBGF parameters, mortality rates, length and age at maturity
	ma'ava	forktail rabbitfish	*Siganus argenteus*	Otolith readability, length frequency, length at maturity

VBGF = von Bertalanffy growth function

3. Results and Discussion

Assessments of otolith readability[2]

Assessments of otolith readability were conducted on otoliths from *Liza macrolepis* (n = 10), *Mugil cephalus* (n = 10) and *Siganus argenteus* (n = 10). Table 2 provides a description of the otoliths of those species with untested readability in the region, and includes notes on their processing for ageing.

[1] Image courtesy of John E. Randall (all other images property of SPC)

[2] Adapted from Robertson and Krusic-Golub 2015. Age estimation of coral reef fish from Pacific Island countries and territories. Fish Ageing Services Pty Ltd Report No. 2015/004. Technical report to the Pacific Community.

Demographic analyses

Ctenochaetus striatus

Fifty-six *Ctenochaetus striatus* were sampled from the spearfishing catch of Tongatapu. The sex ratio was 1 male: 1.9 females (19 males to 27 females). Lengths ranged from 14.2 to 24.0 cm *FL*, with a modal length class of 18.0 – 18.9 cm *FL* (Fig. 1). The average length was 18.3±0.2 cm *FL*. The length-weight relationship was $W = 0.0001 \times FL^{2.528}$.

Ages were assigned to all *C. striatus* sampled. Estimated ages of *C. striatus* ranged from 2 to 40 years, with a modal age of 7 years. No significant difference was observed in age frequency distribution among sexes (X^2 = 19.6, df = 21, p = 0.55). Likelihood ratio tests revealed that growth of *C. striatus* differed significantly among sexes (X^2 = 9.3, df = 2, p = 0.01), with males growing slightly faster and reaching a greater hypothetical asymptotic length than females.

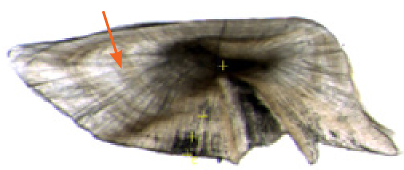
Total mortality for *C. striatus* at Tongatapu was estimated to be 0.12 yr^{-1}. The estimate of *M* from fitting Hoenig's (1983) equation using the maximum observed age of 40 years was 0.10 yr^{-1}. Accordingly, fishing mortality was calculated to be 0.02 yr^{-1}, which is below the maximum optimal fishing mortality rate of 0.05 yr^{-1} (Table 4).

Due to low numbers of immature individuals, no estimates of length or age at maturity were established for this species.

Lethrinus obsoletus

Sixty-three *Lethrinus obsoletus* were sampled from the fish fence (n = 16) and spearfishing (n = 47) catch of Tongatapu; all of which were assigned an age. The sex ratio was largely skewed towards females, with males representing 6 of the 63 individuals observed in the catch. Observed lengths ranged from 13.1 to 28.0 cm *FL*, with an average length of 21.9 cm *FL*, and a modal length class of 24.0 – 24.9 cm *FL* (Fig. 1). Fish captured by fish fences were significantly smaller than those caught by spearfishing (range = 13.1 – 18.1 cm *FL* vs 21.0 – 28.0 cm *FL*; average = 16.3±0.3 cm *FL* vs. 23.8±0.3 cm *FL* for fish fences and spearfishing, respectively). The length-weight relationship was $W = 0.00001 \times FL^{3.1942}$.

Table 2: Description of otoliths and notes on their processing for species with untested otolith readability.

Species	Description and readability of otoliths	Otolith image[3]
Liza macrolepis	Otoliths of this species were relatively easy to read – opaque zones were relatively clear in transverse sections. The average readability score was 5. Of the 10 samples examined, all individuals were estimated to be 2 years of age. Greater sampling of larger, older fish is required to assess their readability.	
Mugil cephalus	Otoliths of this species were relatively difficult to read – opaque zones were quite diffuse, with lots of radial striae present. The first zone was often difficult to determine. The average readability score was 5. Of the 10 samples examined, estimated ages ranged from 2 – 3 years. Greater sampling of larger, older fish is required to assess their readability.	
Siganus argenteus	Otoliths from *S. argenteus* are very small and thin. Opaque zones were identifiable in transverse sections, usually regular in appearance, but diffuse on the outer edge, making readability difficult. The average readability score was 5. Due to their small size and fragile nature, otoliths require individual hand ground sectioning. Otoliths could potentially be read whole, saving costly and time-consuming individual sectioning, although greater sample sizes are required to compare the annuli counts from whole otolith reads to those from sectioned otoliths. Of the 10 samples examined, estimated ages ranged from 4 – 9 years.	

[3] Images from Robertson and Krusic-Golub 2015. Orange arrows indicate the assumed first annual opaque zone and yellow crosses indicate otolith core and subsequent zones.

Estimated ages for *L. obsoletus* at Tongatapu ranged from 0 to 16 years, with a modal age of 3 years. As with lengths, fish captured by fish fences were significantly younger than those caught by spearfishing (range = 0 – 1 years vs 2 – 16 years; average = 0.9±0.1 years vs 5.4±0.5 years for fish fences and spearfishing, respectively).

After an initial period of rapid growth, *L. obsoletus* at Tongatapu were relatively slow-growing, which is consistent with observations of this species elsewhere (e.g. Ebisawa and Ozawa 2009; Taylor 2010). Total mortality was estimated to be 0.19 yr^{-1}. Natural mortality estimated from the Hoenig (1983) equation using a maximum age of 21 years (Ebisawa and Ozawa 2009) was 0.20 yr^{-1}, suggesting a poor fit to the mortality calculations. As such, no estimates of fishing mortality were established for this species. Greater sampling of this species is required to confirm mortality rates and its population status in Tongatapu.

Length and age at maturity was established for female *L. obsoletus* at Tongatapu. The length at which 50% of females became mature was estimated to be approximately 22.3 cm *FL*, while 95% of the population was estimated to be mature at 23.6 cm *FL* (Table 5). The age at which 50% of females became mature was 2.9 years, while 95% of females were mature by 3.2 years (Table 5).

Lutjanus fulvus

Twenty-four *Lutjanus fulvus* were sampled from the commercial catch at Tongatapu, all of which were aged. The sex ratio was 1 male: 2 females (8 males to 16 females). Lengths ranged from 17.9 to 28.4 cm *FL*, with a modal length class of 24.0 – 24.9 cm *FL*. The average length was 23.4 ± 0.5 cm *FL*. The length-weight relationship was $W = 0.00003 \times FL^{2.8293}$.

Estimated ages of *L. fulvus* ranged from 2 to 25 years, with a modal age of 2 years. Growth differed significantly among sexes ($X^2 = 10.2$, df = 2, $p = 0.006$), with females reaching a greater asymptotic length than males, and males growing slightly faster than females (Table 3). Due to low sample sizes, no estimates of mortality or maturity were established for this species. Greater sampling of this species is required to confirm mortality rates and its population status in Tongatapu.

Naso lituratus

One hundred and ten *Naso lituratus* were sampled from commercial spearfishers of Tongatapu. Lengths ranged from 16.1 to 26.5 cm *FL*, with a modal length class of 21.0 – 21.9 cm *FL* (Fig. 1). The average length was 20.9±0.2 cm *FL*. The average length of males was slightly larger than females (21.3±0.3 cm *FL* for males vs. 20.5±0.3 cm *FL* for females).

Ages were assigned to 106 of the 110 *N. lituratus* collected. Estimated ages for *N. lituratus* ranged from 1 – 4 years, with a modal age of 2 years (Fig. 2). The maximum observed age (4 years) was considerably lower than that observed for elsewhere in the region (e.g. Palau = 13 years, Moore et al. 2015; Cook Islands = 14 years, SPC unpublished data). No significant difference was observed in the age frequency distributions between sexes ($X^2 = 1.4$, df = 3, $p = 0.71$).

Growth in both sexes was initially very rapid, consistent with observations of this species elsewhere across its distribution (Taylor et al. 2014; Moore et al. 2015). Likelihood ratio tests revealed that growth of *N. lituratus* differed significantly by sex ($X^2 = 9.3$, df = 3, $p = 0.03$), with males typically growing faster and reaching a greater asymptotic length than females (Table 3).

The estimate of total mortality (*Z*) for *N. lituratus* at Tongatapu was extremely high at 1.29 yr^{-1}. This estimate far exceeds total mortality estimates for this species elsewhere in the region. For example, Taylor et al. (2014) estimated total mortality of *N. lituratus* to be 0.33 and 0.40 $year^{-1}$ in Pohnpei and Guam, respectively, while Moore et al. (2015) estimated total mortality to be 0.41 $year^{-1}$ in Palau. The estimate of *M* from fitting Hoenig's (1983) equation using a maximum age of 14 (based on samples from the nearby Cook Islands) years was 0.30 yr^{-1}. Accordingly, fishing mortality was calculated as 0.99 yr^{-1}; more than six times the maximum optimal fishing mortality rate of 0.15 yr^{-1}. These results indicate that *N. lituratus* populations at Tongatapu are fished well beyond a sustainable level, suggesting that urgent and decisive management action is needed to reduce fishing pressure on this species.

Length and age at maturity was established for both female and male *N. lituratus* at Tongatapu. For females, length at which 50% of the population is mature was approximately 18.6 cm *FL*, while 95% of the population was estimated to be mature at 20.0 cm *FL*. The length at which 50% of males became mature was 20.3 cm *FL*, while 95% of males were mature by 20.9 cm *FL* (Table 5). Maturity of both females and males occurred early in life. The age at which 50% of females became mature was 0.9 years, while 95% of females were mature by 2.6 years. The age at which 50% of males were mature was 1.4 years, while 95% of the male population was mature by 2.3 years (Table 5).

Naso unicornis

One hundred *Naso unicornis* were sampled from the commercial spearfisher catch of Tongatapu. The sex ratio was 1 male: 1.5 females (40 males to 60 females). Lengths ranged from 14.1 to 51.5 cm *FL*, with an average length of 30.5±0.8 cm *FL* (Fig. 1). The average length of males was slightly larger than females (32.6±1.3 cm *FL* for males vs 29.1±1.0 cm *FL* for females).

Ages were assigned to 96 of the 100 *N. unicornis* sampled. Ages ranged from 0 to 6 years, with a modal age of 2 years (Fig. 2). As with *N. lituratus*, the maximum observed age for *N. unicornis* was considerably lower compared to elsewhere in the region. For example, a maximum age exceeding 30 years has been observed for this species in Australia and Palau (Choat and Axe 1996; Moore et al. 2015), while Taylor et al. (2014) recorded a maximum age of 16 years at Pohnpei and 23 years at Guam. No significant difference was observed in the age-frequency distributions between males and females ($X^2 = 6.2$, df = 6, p = 0.39). As with the congener *N. lituratus*, growth of *N. unicornis* was initially very rapid.

Total mortality for *N. unicornis* was estimated as 0.81 yr^{-1}. Again, these estimates were considerably higher than elsewhere in the region. For example, Taylor et al. (2014) estimated total mortality rates of 0.32 $year^{-1}$ for Pohnpei and 0.16 $year^{-1}$ for Guam, while Moore et al. (2015) estimated total mortality to be 0.16 $year^{-1}$ for populations in Palau. The estimate of *M* from fitting Hoenig's (1983) equation using a maximum age of 30 years (from Choat and Axe 1996) was 0.14 yr^{-1}. Accordingly, fishing mortality was calculated to be 0.67 yr^{-1}; almost 10 times greater than the maximum optimal fishing mortality reference point of 0.07 yr^{-1}. As with *N. lituratus*, these results indicate that *N. unicornis* populations in Tongatapu are also fished far beyond a sustainable level, suggesting that urgent and decisive management action is needed to reduce fishing pressure on this species.

Length and age at maturity was estimated for both female and male *N. unicornis* at Tongatapu. For females, length at which 50% of the population was mature was approximately 28.1 cm *FL*, while 95% of females were estimated to be mature at 33.3 cm *FL*. The length at which 50% of males became mature was 30.8 cm *FL*, while 95% of males were mature by 35.5 cm *FL* (Table 5). The age at which 50% of females became mature was 2.2 years, while 95% of the female population was mature by 3.6 years. The age at which 50% of males were mature was 2.6 years, while 95% of the male population was mature by 3.6 years (Table 5).

Siganus argenteus

In total, 103 forktail rabbitfish (*Siganus argenteus*) were sampled from the commercial spearfishing catch of Tongatapu. The sex ratio was 1 male: 2.03 females (34 males to 69 females). Lengths ranged from 12.9 to 27.8 cm *FL*, with the majority of individuals measuring 16.0 – 20.9 cm *FL* (Fig. 1). The average length was 19.1±0.3 cm *FL*. Due to initial uncertainty in ageing this species (see above), no age-based demographic parameters were estimated for this species.

Length at maturity was established for male and female *S. argenteus* at Tongatapu. For females, length at which 50% of the population is mature was approximately 17.8 cm *FL*, while 95% of the population was estimated to be mature at 20.7 cm *FL* (Table 5). The length at which 50% of males became mature was 18.7 cm *FL*, while 95% of males were mature by 22.7 cm *FL* (Table 5).

Table 3: Demographic parameter estimates for selected reef fish species from Tongatapu, Tonga, July 2014. von Bertalanffy growth function parameters are based on constrained ($t_0 = 0$) estimates.

Species	No. collected	No. aged	Size range (cm *FL*)	Age range	L_∞ (males / females)	*K* (males / females)
Ctenochaetus striatus	56	56	14.2–24.0	2–40	19.26 / 18.31	1.05 / 0.79
Lethrinus obsoletus	63	63	13.1–28.0	0–16	24.54	1.11
Lutjanus fulvus	24	24	17-9–28.4	2–25	23.69 / 25.69	0.81 / 0.72
Naso lituratus	110	106	16.1–26.5	1–4	22.71 / 22.17	1.83 / 1.67
Naso unicornis	100	96	14.1–51.5	0–6	43.29 / 39.75	0.56 / 0.67

Table 4: Estimates of mortality for monitored species using catch curve and Hoenig (1983) estimators. Maximum ages used in the equation of Hoenig (1983) and age ranges used for total mortality (*Z*) calculations are indicated. Fishing mortality rates in green are below estimated maximum optimal rates (F_{opt}), while fishing mortality rates in red exceed maximum recommended rates.

Species	Maximum age (yr)	Observed age range	Total mortality (*Z*)	Natural mortality (*M*)	Fishing mortality (*F*)	F_{opt}	*F:M*
Ctenochaetus striatus	40 (this study)	7 – 22	0.1199	0.1038	0.0161	0.0519	0.155
Lethrinus obsoletus	21 (Ebisawa and Ozawa 2009)	3 – 16	0.1901	0.1989	na	0.0994	na
Naso lituratus	14 (SPC unpublished)	2 – 4	1.2920	0.2996	0.9924	0.1498	3.312
Naso unicornis	30 (Choat and Axe 1996)	2 – 6	0.8099	0.1387	0.6711	0.0694	4.839

na = no estimate available

Table 5: Length and age at maturity for selected species L_{50} and L_{95}: estimated length (cm *FL*) at which 50 and 95% of the population are mature, respectively; A_{50} and A_{95}: estimated age (years) at which 50 and 95% of the population are mature, respectively.

Parameter	Length at maturity		Age at maturity	
	L_{50}	L_{95}	A_{50}	A_{95}
Lethrinus obsoletus				
Females	22.3	23.6	2.9	3.2
Naso lituratus				
Females	18.6	20.0	0.9	2.6
Males	20.3	20.9	1.4	2.3
Naso unicornis				
Females	28.1	33.3	2.2	3.6
Males	30.8	35.5	2.6	3.6
Siganus argenteus				
Females	17.8	20.7	-	-
Males	18.7	22.7	-	-

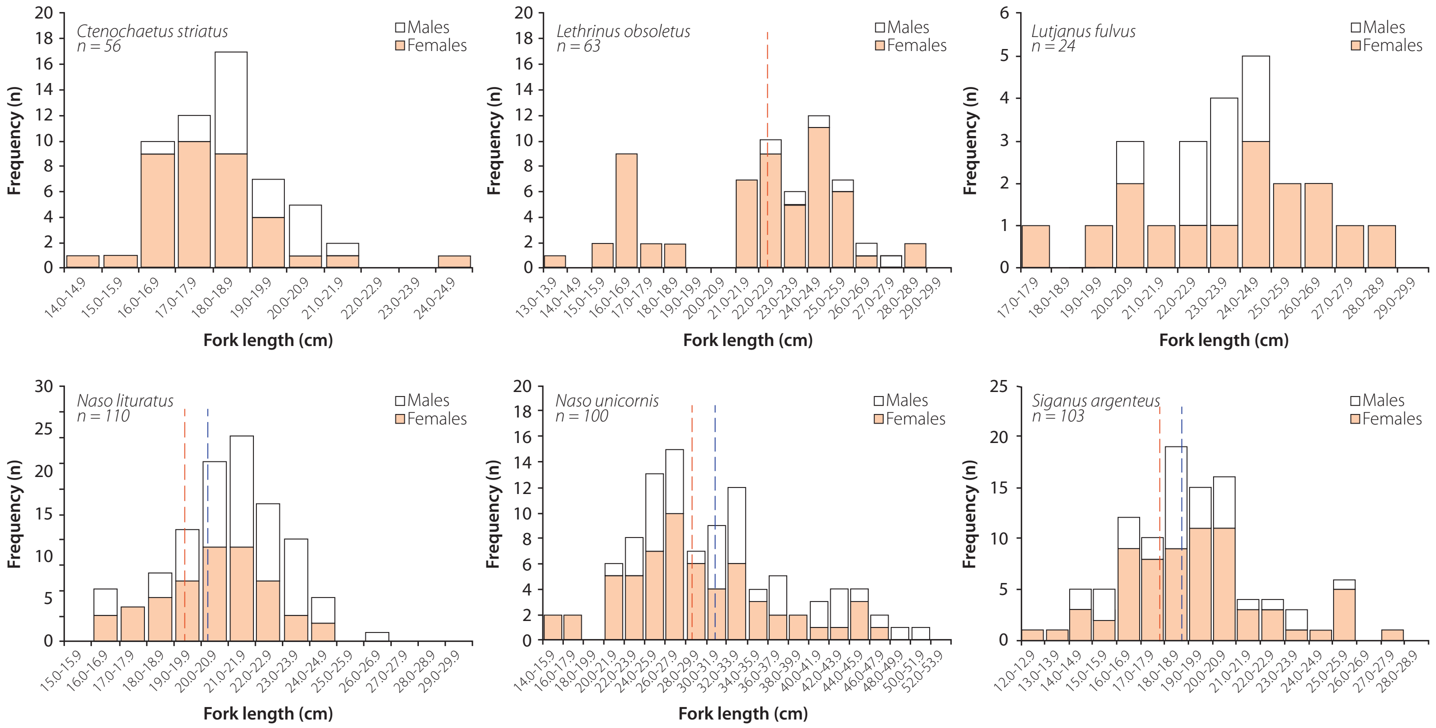


Figure 1: Length-frequency distribution of six exploited finfish species from Tongatapu, Tonga, July 2014. Red lines indicate length at which 50% of females become mature, blue lines indicate length at which 50% of males become mature.

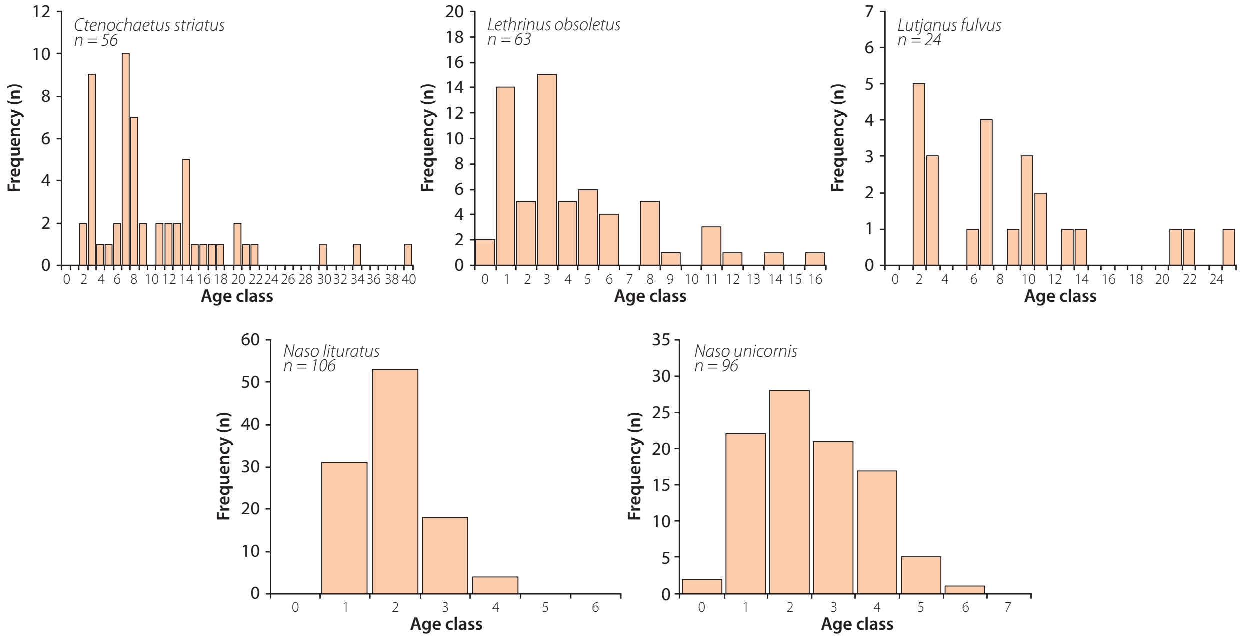


Figure 2: Age-frequency distribution of five exploited finfish species from Tongatapu, Tonga, July 2014.

4. Conclusions and recommendations for management, monitoring and future research

To the best of our knowledge, this report presents the first age-based, demographic assessment of any coastal finfish species of Tonga. Otoliths were generally read with success using standard processing techniques and with a high degree of certainty. This suggests that otolith-based approaches may prove to be useful for assessing the status of coastal finfish species in Tongatapu.

Alarmingly, rates of fishing mortality for the indicator species *Naso lituratus* and *N. unicornis* were found to be approximately six and 10 times greater, respectively, than the optimal recommended fishing mortality rates. This suggests that fishing effort on these two species, and, given their indicator species status, in the night-time spear fishery in general, currently is well above a sustainable level, and needs to be reduced. *Naso lituratus* and *N. unicornis* are highly important food-fish species in Tongatapu and play an important functional role in reducing coral overgrowth and shading by macroalgae, and in preventing and reversing phase shifts from coral-dominated systems to macroalgae-dominated systems (Green and Bellwood 2009). Under the current rates of exploitation, both of these species, and likely many other species in the fishery, are at risk of stock declines and recruitment failure. Without urgent and decisive management attention, the current unsustainable rate of fishing is likely to result in diminished populations and further reductions in the size of remaining individuals of these species, with significant implications for reproductive output, population replenishment, and food security for the people of Tongatapu and for the capacity of reefs in Tongatapu to avoid or reverse unwanted coral-algal phase shifts. Potential strategies for reducing fishing pressure from the night-time spear fishery, and maintaining its long-term sustainability, are discussed below:

1. **Protecting a proportion of the population through marine managed areas**. Marine managed areas (MMAs) and marine protected areas (MPAs) are considered to be highly effective and practical management tools for tropical coral reef fisheries. At the time of writing, three special management areas (SMAs) were in effect in Tongatapu: ‘Atata, ‘Eueiki and Fafa. While Fafa is completely closed to fishing, fishing in ‘Atata and ‘Eueiki is allowed by registered persons, with only a small fraction of these areas considered as ‘no-take’. Together, the areas closed to fishing in these three SMAs (i.e. the areas designated as Fish Habitat Reserves) constitute less than one percent of the inshore fishing grounds of Tongatapu (759 ha of an estimated 94700 ha[4]), while SMAs themselves cover approximately 1.4% of the available area (1,349 ha in total). While the creation of SMAs in Tongatapu is commendable, their small sizes precludes the protection of essential habitat types needed for many species during their life history development and does not account home range sizes or migratory behaviours into account. Accordingly, they are likely to result in only very localised benefits to fished populations at best. Larger scale ‘no-take’ SMAs that link essential habitats for a broad range of species are recommended. Given the small proportion of area involved relative to available fishing grounds, it is unlikely that increases in ‘no-take’ areas will greatly displace or concentrate effort elsewhere. Green et al. (2014) provide a guide to designing marine protected areas to achieve fisheries management and conservation objectives in tropical ecosystems. As a general rule of thumb, they recommend that:

    - MPAs represent 20–40% of the available area of each habitat;
    - protected areas are established across widely separated areas to minimise the risk that all areas will be adversely impacted by the same disturbance; and
    - MPAs be twice the size of the minimum home range of the species they are implemented to protect. For example, most of the browsing or scraping herbivores targeted by night-time spearfishers in Tongatapu have home ranges in the order of 500 m to 5 km (Green et al. 2014).

2. **Enforcing size limits or slots to reduce fishing pressure on the smallest and/or largest individuals.** Many countries and territories in the region are implementing minimum sizes to allow individuals the opportunity to become mature, breed and thus contribute to population replenishment before they are harvested. Similarly, implementation of maximum size limits help protect the largest individuals of the population, which is particularly important given that these individuals contribute a disproportionate amount towards population replenishment through the production of more and fitter eggs and sperm than smaller mature individuals. Additionally, many of the target species in the night-time spearfishing catch (e.g. emperors, parrotfish) are protogynous hermaphrodites (i.e. they start out life as females before

[4] Estimates of the inshore fishing grounds of Tongatapu taken from Lovell and Palaki (2003).

changing sex to males). Implementing a maximum size will offer the largest individuals (i.e. those of the secondary sex) some protection from fishing, thereby reducing the risk of sperm limitation. Introducing size limits could work positively given the inherently high selectivity of night-time spearfishing.

3. **Reduce number of days a vessel can fish.** At present, commercial spearfishing boats in Tongatapu fish between five and six nights per week, every week, with only Sundays and public holidays considered as non-fishing nights. Reducing the number of nights a boat can fish (e.g. no night-spearfishing on Wednesdays) may help to decrease overall fishing pressure. However, to prevent fishers from increasing their fishing pressure on nights they can fish to make up for lost income, this measure may have to be coupled with other strategies (e.g. imposing a nightly catch limit per fisher). In addition, the long-term benefits of this measure to fisheries sustainability must be weighed against the short-term socioeconomic implications to fishers, their families and on down the supply chain (e.g. marketers).

4. **Reduce the number of fishers per vessel.** Similar to reducing the number of days an individual vessel can fish, reducing the number of people participating in a fishing trip could assist to decrease overall fishing effort. Such an approach may prove difficult to enforce however, and again, the long-term benefits of this measure to fisheries sustainability must be considered against the short-term socioeconomic implications to fishers, their families and on down the supply chain (e.g. marketers).

5. **Impose a nightly catch or species bag limits.** As with the introduction of size limits, imposing a nightly catch limit or individual species bag limit (e.g. no more than 10 *N. unicornis* per fisher per trip) could work positively given the high degree of selectivity associated with night-time spearfishing. Again, such an approach may prove difficult to enforce, and the socio-economic implications of this measure on the fishers and down the supply chain must be considered. Rules would also have to be put in place to prevent 'high-grading' (whereby smaller, previously harvested, individuals are discarded for larger individuals).

6. **Improve education and awareness.** Effort should be made by the Fisheries Department to improve fisher and public awareness about reef fish biology, including lengths and ages at maturity, maximum ages and life cycles. These programmes should also describe why and how certain management strategies are needed. A well-informed fishing community and public is more likely to accept appropriate resource management approaches and make better-informed decisions when harvesting or purchasing reef fish. Education and awareness activities should target various people (e.g. children and adults) and in various forms (e.g. posters, pamphlets, videos, radio).

7. **Move fishing pressure away from reef resources.** Shifting fishing pressure onto nearshore pelagic fish has been recognised by many authors to be key to reducing fishing pressure on stressed reef resources. This can be done most effectively by installing a network of low-cost fish aggregating devices (FADs). FADS should be anchored close enough to the coast to provide better access to skipjack and yellowfin tuna. At the same time, incentives should be offered to move fishing effort away from reef resources and onto pelagic resources.

8. **Greater enforcement of existing fisheries management regulations.** Although the biological sampling occurred during the June-July ban on the harvest and sale of mullet (*Mugil* spp.), many vendors were selling freshly caught mullet, with little fear that they would be caught and fined. Increased and randomised routine checks should be conducted by the Monitoring, Control and Surveillance and Licensing section of the Fisheries Department to ensure compliance with the rulings set out in the Fisheries (Conservation and Management) Regulations 1994. Additionally, a review of the powers of authorised officers in current legislation should be conducted, and these powers amended if found to be inadequate for enforcement.

9. **Ban night-time spearfishing.** Night-time spearfishing is a highly over-efficient practice because it targets individuals sleeping on the reef when they are easily visible and accessible to spearfishers. Due to the destructive effect of this practice on fish stocks, many management authorities in the region are moving towards temporary moratoria or complete bans on night-time spearfishing.

Stakeholder consultations should be undertaken to evaluate the potential of the above management options, and determine those that would be most effective, while still maintaining social and economic benefits of the fishery. There is likely to be no single fix for reducing fishing pressure to a sustainable level; a combination of management strategies is likely to be most effective in minimising fishing pressure on Tongatapu's coastal finfish populations.

Recommendations for future monitoring and research

To evaluate the success of any management interventions and well as monitor the status and trends in productivity of Tongatapu's coastal fisheries, continued monitoring is needed. We highly recommend that any monitoring programme focusing on coastal finfish populations include a biological sampling and demographic analysis component. Although traditionally designed for data-rich fisheries, harvest strategies are increasingly being implemented in data-poor scenarios (Smith et al. 2014; Dowling et al. 2015). A harvest strategy could be formalised and a decision framework approach developed to guide management. Clear and simple trigger or reference points could be assigned for each biological parameter of interest to initiate management decisions, such as those in Table 6. We recommend monitoring species-specific annual trends in length and proportion of mature and immature fish in the catch of as many indicator species as possible. Care must be taken to ensure those fish measured are representative of the catch (e.g. by measuring the entire contents of an unopened cooler, rather than selecting individuals). Detailed sampling to develop annual estimates of fishing mortality from species-specific age structures could then be conducted every two years. Priority should be given to the most commonly harvested species.

Table 6: Example of a decision-rule approach to management of coastal fisheries using fishing mortality (*F*) estimates.

Assessment outcome	Example	Decision rule
$F < F_{opt}$	$F < 0.5M$	Maintain current fishing effort or increase effort
$F = F_{opt}$	$F = 0.5M$	Maintain current fishing effort
$F_{opt} < F < F_{limit}$	$0.5M < F < M$	Decrease fishing effort (e.g. 0–50%)
$F > F_{limit}$	$F > M$	Decrease fishing effort substantially (e.g. 50–100%)

In addition to demographic monitoring, we recommend monitoring catches and catch rates within coastal fisheries. From March 2013 to January 2015 the Fisheries Department undertook regular monitoring of the parameters through a creel survey programme that was designed to obtain key basic data on the coastal fisheries of Tongatapu, such as catch, effort, areas fished and gear used. In 2015, it was decided that no further data gathering activities be conducted pending analysis of the current data. These data should be analysed and reported on with the highest priority so that data collection can resume.

The maximum ages used to calculate natural mortality rates in this assessment come from those observed in less intensive fisheries elsewhere the region. As such, they likely to be an underestimation of species' maximum ages relative to that of unexploited populations. This in turn would result in a slight overestimation of natural mortality and a subsequent *underestimation* of fishing mortality. Effort should be made to obtain maximum ages structures for unfished or lightly fished populations, for use in natural mortality equations.

Examination of the length and age structures of *L. obsoletus* captured by the fish fence revealed this method selects for small, young and most importantly immature individuals, with 100% of the *L. obsoletus* catch from the fish fences considered to be immature. That is, fishers harvest individuals before they have a chance to reproduce and contribute to the replenishment of the population. This sample, however, was taken from a single catch. A detailed assessment of the catch from the fish fences should be undertaken to assess the proportion of immature individuals these gear types select for. If the proportion of immature individuals of a species in the catch is too high (e.g. > 30%), these gear types should be modified (e.g. mesh sizes increased), or removed altogether, in the interest of long-term sustainability of fisheries resources in Tongatapu.

5. References

Bell L.A.J., Fa'anunu U. and Koloa T. 1994. Fisheries resources profiles: Kingdom of Tonga. Pacific Islands Forum Fisheries Agency Report 94/5. Forum Fisheries Agency, Honiara, Solomon Islands.

Bell J.D., Johnson J.E., Ganachaud A.S., Gehrke P.C., Hobday A.J., Hoegh-Guldberg O., Le Borgne R., Lehodey P., Lough J.M., Pickering T., Pratchett M.S. and Waycott M. 2011. Vulnerability of tropical Pacific fisheries and aquaculture to climate change: Summary for Pacific Island countries and territories. Secretariat of the Pacific Community, Noumea, New Caledonia. 386 p.

Choat J.H. and Axe L.M. 1996. Growth and longevity in acanthurid fishes; an analysis of otolith increments. Marine Ecology Progress Series 134: 15–26.

Choat J.H., Axe L.M. and Lou D.C. 1996. Growth and longevity in fishes of the family Scaridae. Marine Ecology Progress Series 145: 33–41.

Choat J.H., Kritzer J.P. and Ackerman J.L. 2009. Ageing in coral reef fishes: do we need to validate the periodicity of increment formation for every species of fish for which we collect age-based demographic data? In: Green B.S., Mapstone B.D., Carlos G and Begg G.A. (eds) Tropical fish otoliths: information for assessment, management and ecology. New York: Springer. p 23–54.

Dowling N.A., Dichmont C.M., Haddon M., Smith D.C., Smith A.D.M. and Sainsbury K. 2015. Guidelines for developing formal harvest strategies for data-poor species and fisheries. Fisheries Research 171: 130–140.

Ebisawa A. and Ozawa T. 2009. Life-history traits of eight *Lethrinus* species from two local populations in waters off the Ryukyu Islands. Fisheries Science 75: 553–566.

Friedman K., Pinca S., Kronen M., Boblin P., Chapman L., Magron F., Vunisea A. and Labrosse P. 2009. Tonga country report: Profiles and results from survey work at Ha'atafu, Manuka, Koulo and Lofanga (November and December 2001; March to June 2002, April to June, September and October 2008). Pacific Regional Oceanic and Coastal Fisheries Development Programme (PROCFish/C/CoFish). Secretariat of the Pacific Community, Noumea, New Caledonia.

Green A.L. and Bellwood D.R. 2009. Monitoring functional groups of herbivorous reef fishes as indicators of coral reef resilience – a practical guide for coral reef managers in the Asia Pacific Region. IUCN working group on Climate Change and Coral Reefs. Gland, Switzerland: IUCN. 70 p.

Green A.L., Maypa A.P., Almany G.R., Rhodes K.L., Weeks R., Abesamis R.A., Gleason M.G., Mumby P.J. and White T. 2014. Larval dispersal and movement patterns of coral reef fishes, and implications for marine reserve network design. Biological Reviews 90: 1215–1247.

Haddon M (2001). Modelling and quantitative methods in fisheries. London: Chapman and Hall.

Hoenig J.M. 1983. Empirical use of longevity data to estimate mortality rates. Fishery Bulletin 82: 898–902.

Langi S., Latu T. and Tulua S. 1987. Biological survey of mullets; results of the first six months. Tonga Fisheries Division. 31 p.

Langi S., Latu T. and Tulua S. 1988. Biological survey of mullets; results of the first six months. Information paper 5. Workshop on Inshore Fishery Resources, SPC Noumea. South Pacific Commission, Noumea, New Caledonia. 8 p.

Lovell E.R. and Palaki A. 2003. National coral reef status report Tonga. p 303–329. In: Kulbicki M. Les récifs coralliens du Pacifique : état et suivi, resources et gestion (= Coral reefs in the Pacific: status and monitoring, resources and management). L'Institut de Recherche pour le Developpement (IRD), Noumea, New Caledonia.

Malm T. 2001. The tragedy of the commoners: The decline of the customary marine tenure system of Tonga. SPC Traditional Marine Resource Management and Knowledge Information Bulletin 13: 3–13.

Moore B.R., Rechelluul P. and Victor S. 2015. Creel survey and demographic assessments of coastal finfish fisheries of southern Palau: September 2014. Secretariat of the Pacific Community, Noumea, New Caledonia. 48 p.

Newman S.J. and Dunk I.J. 2002. Growth, age validation, mortality, and other population characteristics of the red emperor snapper, *Lutjanus sebae* (Cuvier, 1828), off the Kimberley Coast of north-western Australia. Estuarine, Coastal and Shelf Science 55: 67–80.

Newman S.J., Williams D.M. and Russ G.R. 1996. Age validation, growth and mortality rates of the tropical snappers (Pisces: Lutjanidae), *Lutjanus adetii* (Castelnau, 1873) and *L. quinquelineatus* (Bloch, 1790) from the central Great Barrier Reef. Australian Journal of Marine and Freshwater Research 47: 575–584.

Pilling G.M., Millner R.S., Easey M.W., Mees C.C., Rathacharen S. and Azemia R. 2000. Validation of annual growth increments in the otoliths of the lethrinid *Lethrinus mahsena* and the lutjanid *Aprion virescens* from sites in the tropical Indian Ocean, with notes on the nature of growth increments in *Pristipomoides filamentosus*. Fishery Bulletin 98: 600–611.

R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Ricker W.E. 1975. Computation and interpretation of biological statistics of fish populations. Fisheries Research Board of Canada 191. 382 p.

Robertson S. and Krusic-Golub K. 2015. Age estimation of coral reef fish from Pacific Island countries and territories. Fish Ageing Services Pty Ltd Report No. 2015/004. Technical report to the Secretariat of the Pacific Community.

Shimose T. and Nanami A. 2014. Age, growth and reproductive biology of blacktail snapper, *Lutjanus fulvus*, around the Yeyama Islands, Okinawa, Japan. Ichthyological Research doi: 10.1007/s10228-014-0401-3.

Smith A.D.M., Smith D.C., Haddon M. Knuckey I.A., Sainsbury K.J. and Sloan S.R. 2014. Implementing harvest strategies in Australia: 5 years on. ICES Journal of Marine Science 71: 195–203.

Taylor B.M. 2010. Life-history and per-recruit assessment of *Lethrinus obsoletus* from Guam. University of Guam Marine Laboratory Technical Report 128. 16 p.

Taylor B.M., Rhodes K.L., Marshell A. and McIlwain J.L. 2014. Age-based demographic and reproductive assessment of orangespine *Naso lituratus* and bluespine *Naso unicornis* unicornfishes. Journal of Fish Biology 85: 901–916.

Tonga Department of Statistics. 2015. http://www.spc.int/prism/tonga/. Last accessed 30th July 2015.

Trip E., Choat J.H., Wilson D.T. and Robertson D.R. 2008. Inter-oceanic analysis of demographic variation in a widely distributed Indo-Pacific coral reef fish. Marine Ecology Progress Series 373: 97–109.

Walters C. 2000. Stock assessment needs for sustainable fisheries management. Paper presented at the Third William R. and Lenore Mote International Symposium in Fisheries Ecology entitled 'Targets, Thresholds, and the Burden of Proof in Fisheries Management'. 31 October–2 November 2000, Mote Marine Laboratory, Sarasota, Florida.

Wilkinson W.A. 1977. Fisheries Division Annual Report – 1997. Department of Agriculture, Forestry and Fisheries, Kingdom of Tonga.