The status of sea cucumber stocks in the Kingdom of Tonga

George Shedrawi, Pauline Bosserelle, Siola'a Malimali, Viliami Fatongiatau, Sione Mailau, Franck Magron, Tevita Havea, Senituli Finau, Samisoni Finau, Penikoni Aleamotua, and Andrew Halford

Pacific Community
Communauté du Pacifique
UNION EUROPÉENNE
Sweden Sverige
NEW ZEALAND FOREIGN AFFAIRS & TRADE Aid Programme
MINISTRY OF FISHERIES TONGA
PEUMP Pacific-European Union Marine Partnership Programme
FAME Fisheries, Aquaculture and Marine Ecosystems Division

The status of sea cucumber stocks in the Kingdom of Tonga

George Shedrawi, Pauline Bosserelle, Siola'a Malimali, Viliami Fatongiatau, Sione Mailau, Franck Magron, Tevita Havea, Senituli Finau, Samisoni Finau, Penikoni Aleamotua, and Andrew Halford

Pacific Community
Communauté du Pacifique

Noumea, New Caledonia, August 2020

Original text: English

Pacific Community Cataloguing-in-publication data

Shedrawi, George

The status of sea cucumber stocks in the Kingdom of Tonga / George Shedrawi, Pauline Bosserelle, Siola'a Malimali, Viliami Fatongiatau, Sione Mailau, Franck Magron, Tevita Havea, Senituli Finau, Samisoni Finau, Penikoni Aleamotua, and Andrew Halford

1. Sea cucumbers — Tonga.

2. Trepang fisheries — Tonga.

3. Holothurian populations — Tonga.

I. Shedrawi, George II. Bosserelle, Pauline III. Malimali, Siola'a IV. Fatongiatau, Viliami V. Mailau, Sione VI. Magron, Franck VII. Havea, Tevita VIII. Finau, Senituli IX. Finau, Samisoni X. Aleamotua, Penikoni XI. Halford, Andrew XII. Title XIII. Pacific Community

593.96099612 AACR2

ISBN: 978-982-00-1280-6

Cover picture: White teatfish *Holothuria fuscogilva* © Viliami Fatongiatau

Prepared for publication and printed at SPC's headquarters,
B.P. D5, 98848 Noumea Cedex, New Caledonia, 2020

www.spc.int

Contents

Foreword

Management for the sustainable use of the fishery resources of the Kingdom of Tonga is of paramount importance to the Ministry of Fisheries. Among these resources, the sea cucumber holds a special place. It is an easily accessible resource because it lives in coastal areas and only requires basic fishing gears to be collected. In addition, it is a high export value resource that contributes to the livelihoods of the people of Tonga, and particularly to coastal communities. For all these reasons, and to make sure the sea cucumber fishery will remain a valuable resource for the communities of Tonga, it is essential for the Ministry of Fisheries to properly manage this fishery, with care and determination, based on scientific evidence. Before the opening of the sea cucumber fishery, The Ministry of Fisheries, in collaboration with the Pacific Community (SPC), conducted field surveys of sea cucumber populations and reef habitats in Vava'u, Ha'apai, and Tongatapu to measure the level of recovery since the initiation of the moratorium in 2014. A total of 189 stations were completed covering 90,720 square meters. Information on the density, size, and distribution of sea cucumber was collected and staff from the Ministry of Fisheries of Tonga visited Noumea, New Caledonia, to work with SPC's Coastal Fisheries Programme to analyse data and complete the stock assessment. The purpose of this report is to communicate those findings and share information on the status of sea cucumber populations.

Summary

- Overall sea cucumber population densities including high, medium, and low market value species observed in 2019 have not recovered sufficiently to support a fishery.
- Adult densities, above size at maturity (L_{50}), for the many species remain severely depleted across much of Tonga.
- High value species *Holothuria whitmaei* (huhuvalu 'uli'uli), *H. fuscogilva* (huhuvalu hinehina) and *H. lessoni* (nga'ito) were recorded in 2016 and 2019, but at very low densities.
- Densities for all species encountered during the 2019 survey were below regional reference densities for healthy stocks – in some cases, at least 20 times lower. For example, surveys of 189 reef benthos transect stations, covering over 90,000 square metres of reef habitat, found eight individuals of the high value species *H. lessoni* (nga'ito) with only three of these larger than size at maturity (L_{50}) 220 mm.
- Length data showed an increase in the number of smaller *H. atra* in 2019, which indicates possible recruitment. However, as a result of heavy harvesting pressure, large individuals of this species have not been recorded since 2007.
- The Special Management Area (SMA) O'ua had relatively high densities of medium and low value species. This is likely due to a combination of the local communities' efforts to control excessive harvesting through the early and proactive implementation of the SMA, as well as it being an ideal habitat for the observed species.
- A higher proportion of smaller individuals of *Stichopus chloronotus* (holomumu) and *Bohadschia argus* (matamata) in 2019 suggests recruitment to these populations has occurred since the moratorium.

Management recommendations

- The introduction of the moratorium on both harvesting and exporting in late 2015 has removed fishing pressure on stocks and enabled some low and medium value species to begin recovering. However, given the continuing poor status of most sea cucumber species across Tonga, it is recommended that the existing moratorium remain in place for another 5 years, and then a fishery-independent survey be completed in 2023 to calculate whether densities of valued species have returned to healthy reference densities and could potentially be sustainably harvested.
- Where populations can be considered healthy enough for sustainable harvesting, we suggest revising minimum harvest lengths such that they are at least 20% above length at maturity (L_{50}). If such data is not available for a specific species, then closely related species could be used to generate appropriate lengths.
- If opening the fishery is unavoidable, it is recommended that the Ministry of Fisheries (MOF) develop a list of permissible species eligible for harvest. Part of eligibility criteria should be that the list should only include species that have a significant proportion of their population larger than L_{50} or above the minimum legal size (MLS). Other eligibility criteria should include their biological characteristics such as growth rate, their densities relative to reference densities, and their status on the International Union for Conservation of Nature (IUCN) Red List or their listing in Appendix II of the Convention on International Trade in Endangered Species (CITES).

Acknowledgements

The assessment and training detailed in this paper was supported by funding under the Pacific European Union Marine Partnership Programme and the New Zealand Ministry of Foreign Affairs and Trade, with support provided by the Tonga Ministry of Fisheries (MoF). The authors would like to thank MoF staff including Ione Finaau, Amanda Le'ota, Moses Moala, and Ofa (Texas) Napa'a for their contribution in all aspects of the field work. The survey would not have been possible without their active and efficient involvement.

This publication has been produced with the financial assistance of the European Union (EU) and the Government of Sweden. Its contents are the sole responsibility of the Pacific Community (SPC) and do not necessarily reflect the views of the European Union or the Government of Sweden.

Introduction

The Kingdom of Tonga is an archipelago consisting of approximately 170 islands. It has an estimated land area of 749 km^2 surrounded by an exclusive economic zone of 676,401 km^2. There are three main island groups: Vava'u, Ha'apai and Tongatapu, which are home to approximately 100,000 people, with 85% living less than 1 km from the coast[1]. The total coastal area of the Tongan Archipelago is approximately 5870 km^2, and is made up of mixed shallow water (< 30 m depth) coral reef, sand, mangroves, and lagoon seagrass habitats, which support subsistence and predominantly artisanal invertebrate and reef-fish fisheries (Friedman et al. 2004; Salcone et al. 2015).

Bêche-de-mer, the processed version of sea cucumber, has historically been the main invertebrate export fishery in Tonga. A total of 26 described species have been observed during surveys in the shallow water lagoon and reef front habitats around Tonga (Lokani et al. 1996; Friedman et al. 2011; Moore et al. 2017), with many of these harvested for the commercial bêche-de-mer trade (Friedman et al. 2011).

Most species of sea cucumbers found in the Pacific Islands region reproduce sexually and have separate sexes, although some species are sequential hermaphrodites, changing from males to females (Lawrence and Herrera 2000). A few species found in the Pacific, including *Holothuria atra, H. edulis, Stichopus chloronotus, S. horrens* and *Bohadschia marmorata*, are known to reproduce asexually (Charan-Dixon et al. 2019; Dolmatov 2014). Sea cucumbers live for approximately 5 to 10 years, although some slow growing species may live to 15 years (Sewell 1990; Sloan 1984). Most species attain sexual maturity at two to six years, although heavy fishing pressure is thought to reduce the size and age at sexual maturity of some species, resulting in the reduction of the maximum growth size (Charan-Dixon 2016; Charan-Dixon et al. 2019).

Easy access to sea cucumber habitats combined with their biological characteristics and the effect of large-scale fisheries on the breeding populations have made some sea cucumbers especially vulnerable to overexploitation. Most sea cucumber species are broadcast spawners, which need relatively high densities of reproductively mature adults to produce high rates of successful fertilisation and subsequent recruitment of new animals into the population; this increases recovery rates or improves resilience against extraction within a fishery. Over-harvesting lowers densities, which decreases fertilisation levels and inhibits population recovery due to the lower probability of fertilisation of released gametes.

If densities become low enough, fertilisation, recruitment, and subsequent replenishment of populations can be severely impeded or absent: an outcome known as the "Allee" effect (Allee 1938; Friedman et al. 2011; Kinch et al. 2008; Purcell et al. 2013). These animals also play a key role in maintaining ecosystem services through bioturbation and nutrient cycling; hence recent documented declines in populations have led to increasing concerns about the potential indirect effects on ecosystem health (Anderson 2010; MacTavish et al. 2012; Michio et al. 2003; Purcell et al. 2016).

Harvesting of sea cucumbers and their sale as bêche-de-mer has been an important source of income for the people of Tonga since the early 1980s. However, consecutive years of large harvests have significantly depleted sea cucumber populations, and a boom–bust fishery cycle has been observed over the last three decades (Friedman 2004, 2011; Pakoa et al 2013). In 1990, the Pacific Community (SPC) working with Tonga Fisheries, conducted a survey to assess stocks of sea cucumbers and found densities of many species were at levels that could support a small-scale bêche-de-mer fishery. Subsequent exports of bêche-de-mer were steady in the 1990s until 1996 when a resurvey to assess the effect of the fishery on standing stocks showed significant declines in sea cucumber populations, particularly for high value species. As a result, the Government of Tonga closed the sea cucumber fishery for 10 years to allow stocks to recover, effective from 31 December 1997.

A follow-up survey in 2004 found that stocks, with the exception of the slow-growing black teatfish *Holothuria whitmaei,* had recovered sufficiently to reopen a sustainable small-scale fishery, provided that an appropriate fisheries management plan was developed and implemented. The sea cucumber fishery was therefore reopened in 2008, only for stocks to decline to their lowest recorded densities (Pakoa et al. 2013). Export data showed that as high value species were depleted, catches of medium and low value species increased, including species that were previously caught for subsistence only (e.g. snakefish, dragon fish, see also Charan-Dixon, 2016; Charan-Dixon et al., 2019). In March 2011, the recorded declines prompted preliminary advice from SPC to the Ministry of Fisheries, recommending the closure of the fishery for a minimum of three to five years to allow stocks to recover. However, the fishery remained open for another five seasons from 2011 to 2015, which subsequently reduced existing breeding populations of all low, medium, and high value species, thereby prolonging the time required for stocks to recover. During these five seasons, the Ministry also increased the length of the open season, which placed further pressure on remaining stocks. Despite the prolonged fishing season, exports declined, prompting the Ministry to place another moratorium on the fishery in October 2015.

1 http://sdd.spc.int/mapping-coastal (Date accessed 10/12/2019)

Tonga's sea cucumber fishery resources have been closely monitored since the 1990s, providing a rare opportunity to assess the effect of two moratoria on stock recovery, the first being 10 years in duration and the second ongoing moratorium being three and a half years at the time of this survey. This report presents the results of a fishery-independent survey three and a half years after the initiation of the second moratorium and compares these results with previous surveys before and after the introduction of the moratorium (Moore et al. 2017; Pakoa et al. 2013). The intention of the moratorium on harvesting and exporting sea cucumbers was to provide sufficient time for stocks to rebuild; previous surveys provide vitally important data for building time series and reference points. This study addresses questions important for understanding population recovery since the initiation of the moratorium.

1. Have sea cucumber densities recovered to levels consistent with those found before the onset of high exports recorded in the mid-1990s, and if not, are they at levels consistent with those recorded after the 10-year moratorium?
2. Are densities similar to species-specific regional reference densities used for assessing population health?
3. Has the relative abundance of the various species of sea cucumbers returned to the historical proportions since the initiation of the moratorium, that is, have higher value species, which were initially the target of catches, increased proportionally to medium and low value species? For example, have *Holothuria fuscogilva* (huhuvalu hinehina), *H. whitmaei* (huhuvalu 'uli'uli), and *H. lessoni* (nga'ito) increased proportionately more than *Bohadschia argus* (matamata), *Stichopus herrmanni* (lomu), *H. atra* (loli) and *H.edulis* (loli pingiki)?
4. Are the length distributions of species populations indicative of a recovered fishery; for example, is there an increase in the abundance of larger individuals?
5. Is there evidence of recruitment occurring within sea cucumber populations; for example, is there an increase in the number of smaller individuals evident?
6. Using the information above, can the current status of standing stock sustain a commercial fishery?

Methods

Survey methods

In-water invertebrate surveys were conducted at Ha'apai, Tongatapu, and Vava'u between February and April 2019. The survey used the reef benthos transect (RBT) method as described by Pakoa et al. (2014). Stations selected were those from earlier surveys by Moore et al. (2017), with additional stations in key habitats to increase replication and measure population variance at appropriate spatial scales for accurate stock assessment across habitats.

RBTs were used to obtain fine spatial scale information on abundance and size (length) of invertebrate species within defined habitats. Each station consisted of six 40 m × 2 m transects aligned in series with a 5 to 10 m gap between each transect (Figure 1). Transect width was doubled from previous surveys to improve statistical power and increase search effort. Surveyed habitat was kept consistent within each station. For example, all transects were completed either on seagrass or on coral reef habitat and at a consistent depth.

Stations were surveyed by three snorkellers or scuba divers, with one diver setting the transect line, one as a data recorder, and one diver photographing the substratum. All sea cucumber encountered were identified to species, tallied, and lengths measured. Due to time constraints, only the lengths of the first 30 individuals of each identified species were measured in each transect, and the remaining individuals encountered were tallied to obtain total abundance. At the end of each day's survey, the data was entered into SPC's Reef Fisheries Integrated Database (RFID).

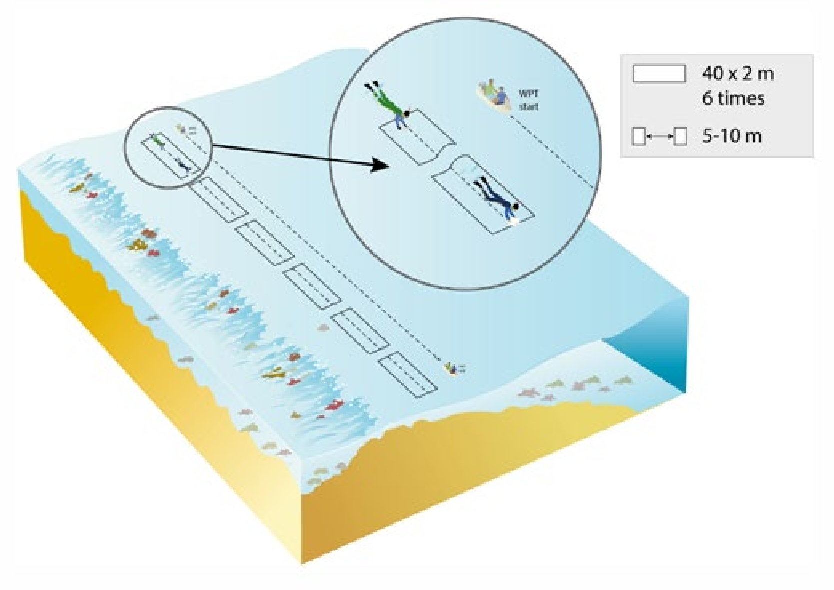
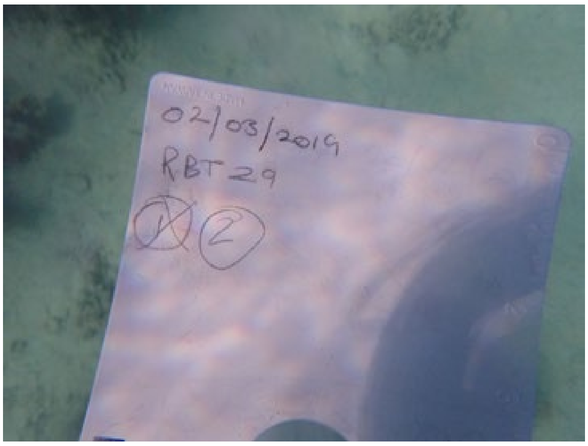


Figure 1. Illustration of the six 40 m by 2 m reef benthos transect (RBT) lines aligned in series along consistent habitat.

To identify the composition and condition of the habitat at each station, a single photo was taken every metre along each transect using a digital underwater camera with 12 megapixel resolution (Figure 2). To ensure each of these "photo-quadrats" were taken from the same height above the substrate, a one-metre calibration rod was attached to the camera (Figure 2). In some situations where there was less than one metre of water depth, the calibration rod was shortened to 50 cm. The camera was set to the widest field of view at all times. Images were analysed for habitat details using the point count method (Abdo et al. 2004).



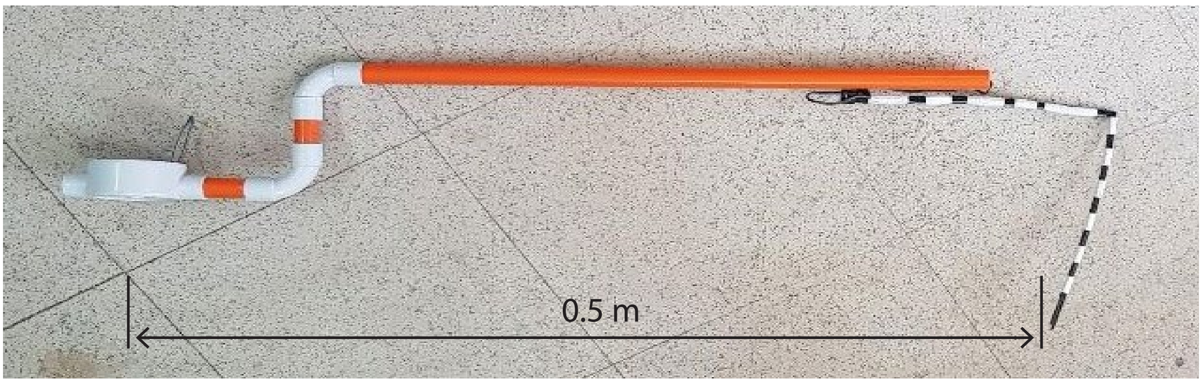


Figure 2. Top Left: Photo of the dive slate after all transects are complete. The information included data, station code, and number of transects, and station start and end waypoint numbers. Top Right: Downward facing view of the substratum and an example of a simple 0.5 m height guide with a black-and-white scale bar that should be present in each image. Bottom: 0.5 m height guide that can be mounted to a camera; black-and-white scale bar that should be present in each photo.

Surveyed area

A total of 189 RBT stations were surveyed in 2019 (Table 1). The total area surveyed at each location was doubled from previous years by increasing transect width from 1 m (240 m^2 per station) to 2 m (480 m^2 per station). The total surveyed area in 2019 was just under twice that in 2016, which increased the likelihood of detecting sea cucumbers across reefs. The survey also included the various habitats found inside and outside the lagoon. Each habitat was classified using standardised geomorphological classifications and the total area for each is given in Table 2. These figures can be used for any future calculations of stock and can be used as a standard in the future.

Table 1. Number of stations surveyed using (A) All methods, and (B) the RBT method, for each year at each island group. Blue shaded years indicate the period before the implementation of the second moratorium on commercial exports.

<table>
<tr><th>A: All methods</th><th>2010</th><th>2011</th><th>2014</th><th>2016</th><th>2019</th></tr>
<tr><td>Vava'u Group</td><td>75</td><td>2</td><td>0</td><td>83</td><td>61</td></tr>
<tr><td>Ha'apai Group</td><td>2</td><td>0</td><td>51</td><td>92</td><td>54</td></tr>
<tr><td>Tongatapu Group</td><td>27</td><td>21</td><td>0</td><td>89</td><td>74</td></tr>
<tr><th>B: reef benthos transect method, mother of pearl transect</th><th colspan="3">(Active fishery – data pooled for abundance and length)</th><th colspan="2">(Moratorium)</th></tr>
<tr><td>Vava'u Group</td><td>49</td><td>0</td><td>0</td><td>49</td><td>60</td></tr>
<tr><td>Ha'apai Group</td><td>0</td><td>0</td><td>27</td><td>64</td><td>54</td></tr>
<tr><td>Tongatapu Group</td><td>10</td><td>4</td><td>0</td><td>69</td><td>74</td></tr>
<tr><td>Total RBT survey area (ha)</td><td>1.416</td><td>0.096</td><td>0.648</td><td>4.638</td><td>9.024</td></tr>
</table>

Table 2. Area in hectares (ha) of each reef geomorphology classification at each island group.

Island	Geomorphology	Area (ha)
Ha'apai Group	back reef	4791
	channels	913
	deep lagoon	13474
	fringing	373
	front reef	110200
	lagoon	12485
	reef flat	10471
Tongatapu Group	back reef	6220
	channels	545
	deep lagoon	2725
	fringing	5198
	front reef	2893
	lagoon	2191
	reef flat	3821
Vava'u Group	back reef	3357
	channels	0
	deep lagoon	2070
	fringing	340
	front reef	3282
	lagoon	2013
	reef flat	3150

Statistical methods

Data collection and analyses

In 2011 and 2014 Vava'u was not surveyed using RBT, and data from the years when the fishery was active (2010, 2011, and 2014) were pooled only using the RBT method at Ha'apai and Tongatapu, and therefore for Vava'u, the years that the fishery was active is only represented by the 2010 survey. Our assumption here is that while fishing pressure may have been different across years and among island groups, for the purposes of this report and building some reference point, these previous surveys during an active fishery had sufficient spatial coverage to compare with the two consistent high-intensity surveys in 2016 (Moore et al 2017) and this survey in 2019.

Tonga has implemented two moratoria on the harvesting and export of sea cucumbers since exports began in the early 1990s. The first moratorium occurred between 1998 and 2007 and the second from 2015 to the present date. Data from the 2016 and 2019 surveys were therefore used to compare with earlier surveys to gain an understanding of how stock has changed through time and, in particular, between when the fishery was active and after the moratorium on exports was initiated in 2015. However, survey methods changed depending on the year surveyed; for example manta tow in some years at some islands groups and/or RBT at other locations and years (Table 1). So to allow meaningful comparisons across years, only the RBT methods were used in length and density analysis. Furthermore, data from the years previous to the initiation of the second moratorium were pooled to gain a sufficient number of stations across Tonga. Pooling of data corresponds to the period when exports were open (i.e. an active fishery from 2010 to 2015). In 2016 a sufficient number of stations were completed across Tonga, and so data from 2016 and 2019 were not pooled. Before 2010, surveys were disparate and an insufficient number of RBT stations were completed across all island groups using comparable methods; therefore only data collected during surveys when the fishery was active from 2010 to 2015 were pooled and tested in density and length comparisons to compare the status of wild stocks during these periods. After the initiation of the moratorium in October 2015, the 2016 survey data were used as a baseline and the 2019 survey data were used to determine if recovery of the sea cucumber population was evident approximately four years after the moratorium was initiated. Comparing survey data from 2016 and 2019 provides the opportunity to assess whether any incremental improvement in stock has occurred, which can also be used to model recovery rates for individual species across Tonga in future.

Generalised linear mixed-effects models (GLMMs) were used to test for differences in the overall (i.e. all species grouped) mean density before the second moratorium (pooled years 2010, 2011, 2015) and after the moratorium (2016 and 2019). GLMMs are more flexible to violations of the traditional assumptions necessary for linear models such as ANOVA. They can accommodate different error structures and are robust to unbalanced survey designs (Pinheiro et al. 2019; R Core Team 2015).

To account for inherent differences in density due to habitat, depth or unmeasured variable type at a location, stations were treated as random effects (i.e. covariates); the time-since-moratorium was treated as a categorical fixed factor with three levels (Active fishery included pooled data from the years 2010, 2011, 2015, First year after the moratorium 2016, and Four years after the moratorium 2019), and density was treated as the response (i.e. dependent variable). Island Group was treated as a fixed factor with three levels, Vava'u, Ha'apai, and Tongatapu. For the purposes of this report we are focussed on the changes in density for each species across the three island groups since the initiation of the moratorium in 2015.

Density data were also compared to regional reference densities for healthy sea cucumber stocks to ascertain if each species' population had recovered sufficiently to support a fishery (Pakoa et al. 2014; Toral-Granda et al. 2008). Historical long-term data from the early 1990s was only available for the Ha'apai island group and the average density per hectare of species for each survey between 1994 and 2019 were compared. Our assumption is that density per hectare taken from the historical literature were calculated from a sufficient number of stations across the various habitats in Ha'apai and therefore comparisons with our data can be made. For more information on statistical techniques, refer to Appendix 1.

Length analysis

Due to the very low number of length measurements carried out between 2010 and 2015, the data from different island groups from 2010 to 2015 were pooled. Data at each island group were also depauperate for some species in 2016 and 2019, so length measurements between island groups were also pooled. Data were then compared between years when exports were open (2010 to 2015) and after the moratorium when exports were closed, 2016 and 2019. Not all island groups were surveyed when the fishery was active, so comparisons of length data between island groups could not be made. Boot-strapped Kolmogorov–Smirnov tests (KS tests) were used to test for significant differences in the size distribution of individual species only between when the fishery was active and since the second moratorium was implemented. The bootstrap KS test is insensitive to ties with non-continuous data, which is inherent in length data collected using bins of 5 mm (Ogle 2016; Sekhon 2008). Additionally, using a bootstrapped calculation of error is robust against unequal sample sizes and traditional assumptions of normality (Ogle 2016; Sekhon 2008). Model details are not included in this document but there is a dedicated website called FishR (http://derekogle.com/fishR/) where interested persons will find extensive information on the analysis of length frequency data. All analyses were done using the R software package (https://www.R-project.org).

Capacity development

Capacity building and training in survey design and implementation, data entry, extraction and analysis for Ministry of Fisheries (MOF) staff took place before, during, and at the completion of the field survey.

Before the survey, a presentation and hands-on instruction between Tonga fisheries staff and SPC staff took place over two days. Training in historical data review and how this is used for planning surveys was completed. Survey design, including habitat selection, survey methods, and logistics were discussed and demonstrated.

During the survey, daily briefs and training in data collection and entry into the Reef Fish ID (RFID) database were completed with MOF staff. The set-up and application of survey equipment, transect placement, and search techniques were demonstrated and tested.

Results

Species composition

A total of 21 species of sea cucumber were observed between 2010 and 2019 with all high value species still observed in 2016 and 2019 (Table 3). The number of species observed when the fishery was active between 2010 and 2014 were also observed in 2016 and 2019 (Table 3). Although the density and range of many species was low, there was no evidence to suggest a loss of species. However, when compared with individual years during active fishing, there were more species observed in 2016 and 2019, likely the result of an increase in RBT survey area in 2016 and 2019 (Table 3).

The relative abundance of sea cucumber species changed between 2002 and 2019. From 2002 to 2007 over one-third of the individuals surveyed consisted of high and medium value species. From 2010 to 2014 the proportion of high and medium value species decreased, such that all high and some medium value species were very rare. The survey in 2016 using a high-intensity RBT survey effort indicated that high value and medium value species remained at low abundance. In 2019, there was some evidence that relative abundance was increasing for the low, medium and high value species *Holothuria edulis*, *Stichopus horrens,* and *H. lessoni,* respectively.

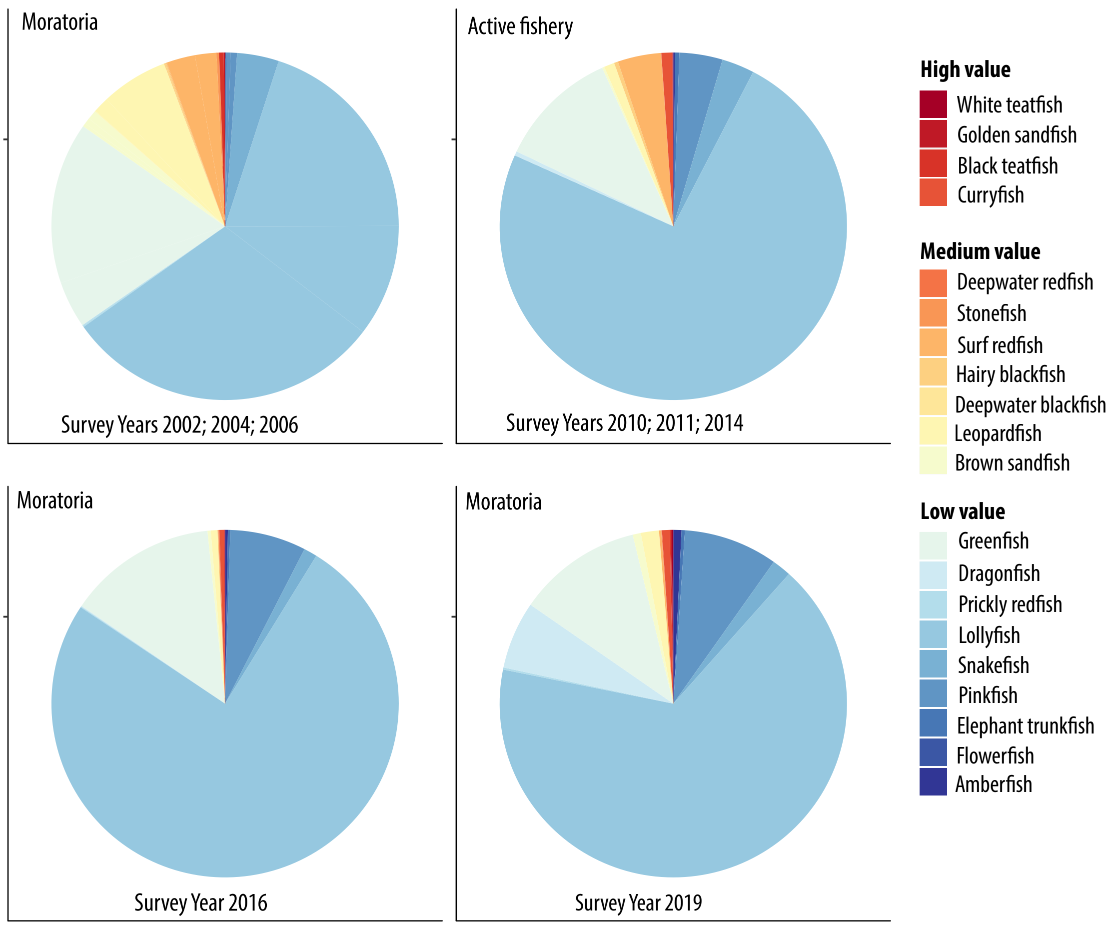


Figure 3. Sea cucumber species composition surveyed in coastal waters of Tonga. Each pie segment represents the abundance of each species over the total abundance. Years were pooled between 2002 and 2006, and between 2010 and 2014, to represent species composition during the moratorium and an active fishery, respectively.

Table 3. Presence of sea cucumber species from surveys completed between 2002 and 2019, categorised by their international market value (Purcell et al. 2017). Characters M and A indicate Moratoria and Active fishery respectively.

Species	Tongan name	Common name	Market Value	IUCN Red list 2	CITES listing	2002 (M)	2004 (M)	2006 (M)	2010 (A)	2011 (A)	2014 (A)	2016 (M)	2019 (M)
Holothuria fuscogilva[*]	Huhuvalu hinehina	White teatfish	High	Vulnerable	Appendix II				✓	✓		✓	✓
*Holothuria lessoni**	Nga'ito	Golden sandfish	High	Endangered		✓			✓	✓		✓	✓
*Holothuria whitmaei**	Huhuvalu 'uli'uli	Black teatfish	High	Endangered	Appendix II			✓		✓		✓	✓
*Stichopus herrmanni**	Lomu curry	Curryfish	High	Vulnerable					✓	✓		✓	✓
Actinopyga echinites#	Telehea kula loloto	Deep water redfish	Medium	Vulnerable					✓			✓	✓
Actinopyga lecanora#	Telehea maka	Stonefish	Medium	Data Deficient				✓	✓			✓	✓
*Actinopyga mauritiana***	Telehea kula mamaha	Surf redfish	Medium	Vulnerable		✓	✓	✓	✓	✓		✓	✓
Actinopyga miliaris#	Loli fulufulu	Hairy blackfish	Medium	Vulnerable		✓		✓			✓	✓	
Actinopyga palauensis#	Mokohunu loli	Deepwater blackfish	Medium	Least Concern								✓	✓
Bohadschia argus[1]	Matamata	Leopardfish	Medium	Least Concern		✓	✓	✓	✓	✓	✓	✓	✓
Bohadschia vitiensis#	Mula	Brown sandfish	Medium	Data Deficient		✓	✓	✓	✓	✓	✓	✓	✓
Stichopus chloronotus[1]	Holomumu	Greenfish	Medium	Least Concern			✓	✓	✓	✓	✓	✓	✓
Stichopus horrens[1]	Lomu	Dragon fish	Medium	Data Deficient				✓	✓			✓	✓
Thelenota ananas[1]	Pulukalia	Prickly redfish	Medium	Endangered			✓	✓	✓			✓	✓
Bohadschia similis	Finemotu'a	Chalkfish	Medium									✓	
Holothuria atra[1]	Loli	Lollyfish	Low	Least Concern		✓	✓	✓	✓	✓	✓	✓	✓
Holothuria coluber#	Tungongo	Snakefish	Low	Least Concern		✓			✓	✓	✓	✓	✓
Holothuria edulis[1]	Loli pingiki	Pinkfish	Low	Least Concern		✓		✓	✓	✓	✓	✓	✓
Holothuria fuscopunctata#	Elefanite	Elephant trunkfish	Low	Least Concern				✓	✓	✓		✓	✓
Pearsonothuria graeffei#	Lomu matala	Flowerfish	Low	Least Concern								✓	
Thelenota anax[1]	Saieniti	Amberfish	Low	Data Deficient					✓	✓		✓	✓

[1] Included in the length analysis.
[2] https://www.iucnredlist.org/ date accessed 30/01/2020
*Low density included as a high value species.
**Low density included in plots as a commercially important species and to serve as a baseline to compare with future surveys.
#Low densities were excluded from length comparisons or bootstrap Kolmogorov–Smirnov tests (less than 10 individuals).

Density and distribution

Sea cucumbers were present at all stations in Vava'u, but were entirely absent at eighteen and four stations in the Ha'apai and Tongatapu island groups respectively. The Tongatapu Group also had a greater number of stations with low densities than either Vava'u or Ha'apai (Figures 4 to 6).

In Vava'u, relatively high densities (greater than 10,000 individuals ha^{-1}) were recorded at three stations located on the eastern side of the island group (south of Ofu Island and east of 'Eueiki) (Figure 4). In Ha'apai, high densities were recorded at a single station in the seagrass areas of 'O'ua (Figure 5). Five stations recorded medium densities (between 1000 and 10,000 individuals ha^{-1}), three of which were also located in proximity to 'O'ua island and a further two on the seagrass areas of Ha'ano Island (Figure 5).

Similar to those on Vava'u, high densities were recorded at three stations east of the Fafa Island SMA in Tongatapu (Figure 6). Stations with low densities (less than 1000 individuals ha^{-1}) were numerous and common within the entire island group. Medium densities were recorded at stations concentrated in the central area of Tongatapu between the shore and Malinoa Island, with the exception of one station close to 'Ata Island (Figure 6).

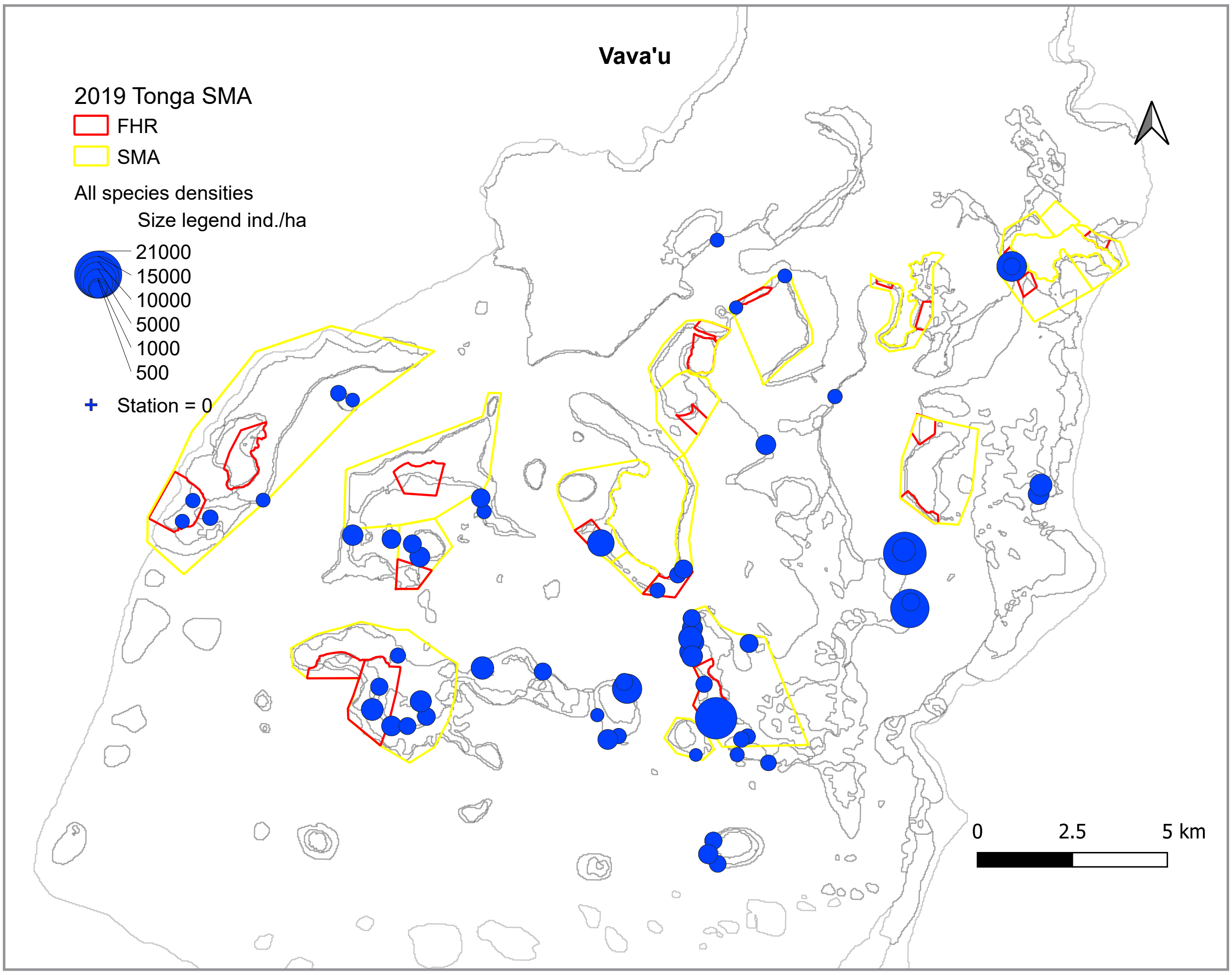


Figure 4. Map indicating location of stations surveyed in 2019: size of the blue marker indicates the relative densities (ha^{-1}) at each station across the Vava'u island group. Yellow and red polygons represent Special Management Areas (SMA) and Fish Habitat Reserves (FHR) respectively.

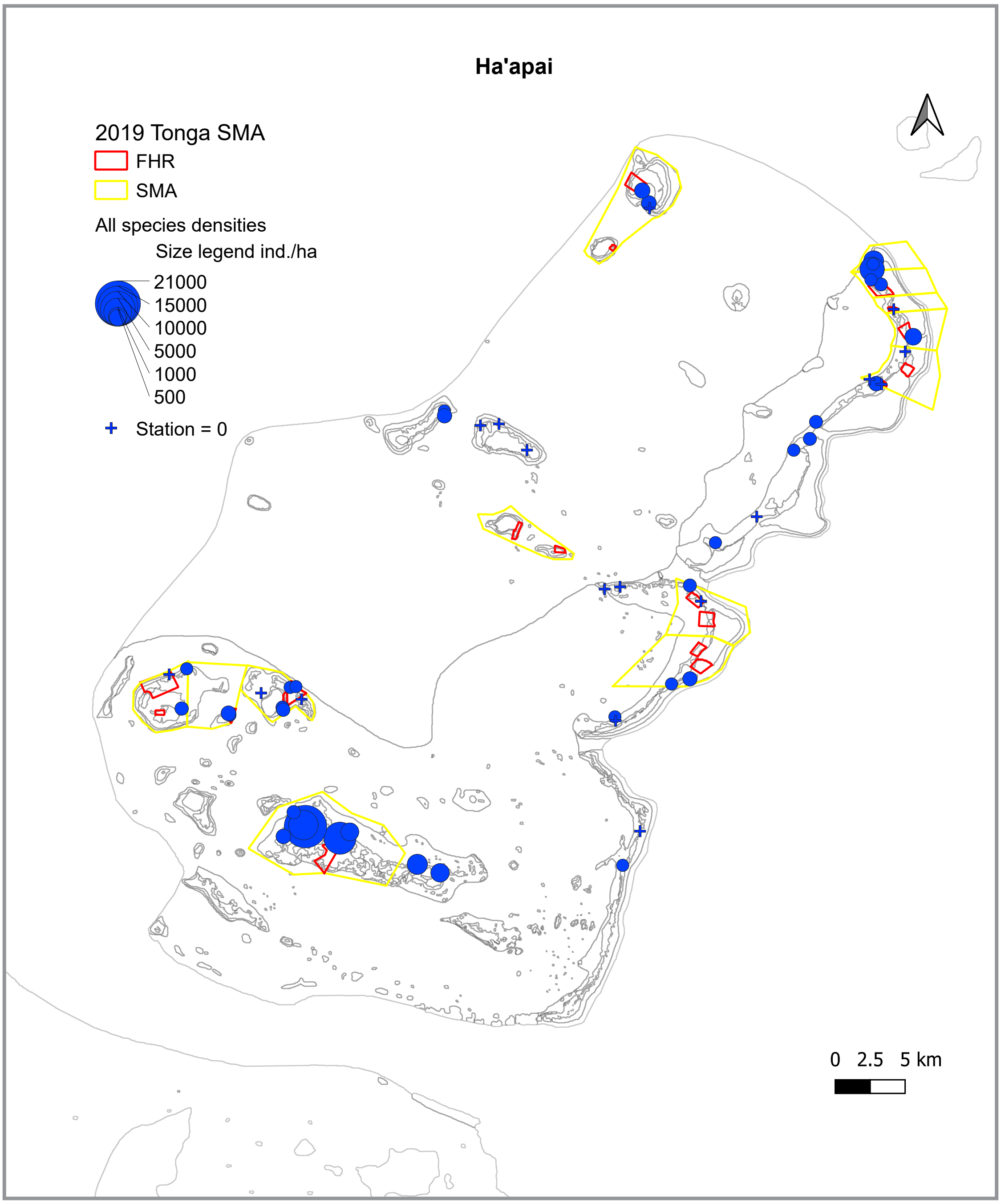


Figure 5. Map indicating location of stations surveyed in 2019: size of the blue marker indicates the relative densities (ha-1) at each station across the Ha'apai island group. Yellow and red polygons represent Special Management Areas (SMA) and Fish Habitat Reserves (FHR) respectively.

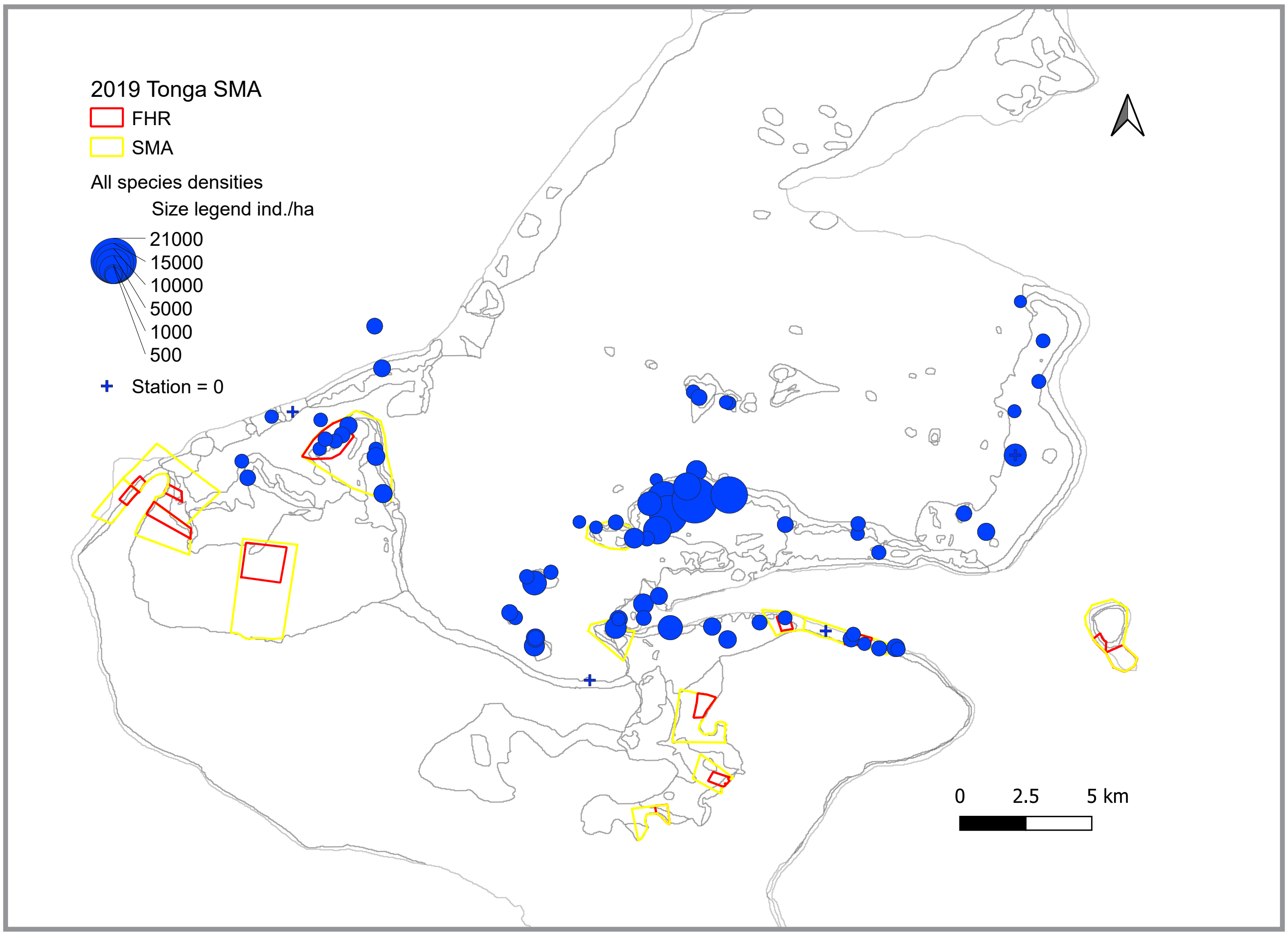


Figure 6. Map indicating location of stations surveyed in 2019: size of the blue marker indicates the relative densities (ha-1) at each station across the Tongatapu island group. Yellow and red polygons represent Special Management Areas (SMA) and Fish Habitat Reserves (FHR) respectively.

In the Tongatapu island group the mean density per hectare of sea cucumbers in 2019, four years after the moratorium was put in place, was significantly greater (ANOVA $p < 0.05$) than the mean density when the fishery was active (Figure 7). In the Ha'apai island group, mean density was significantly lower in 2016 and 2019 than previous years. In contrast to the other island groups, there was no significant change in mean density in the Vava'u island group from when the fishery was active to when the moratorium had been in place for 1–4 years.

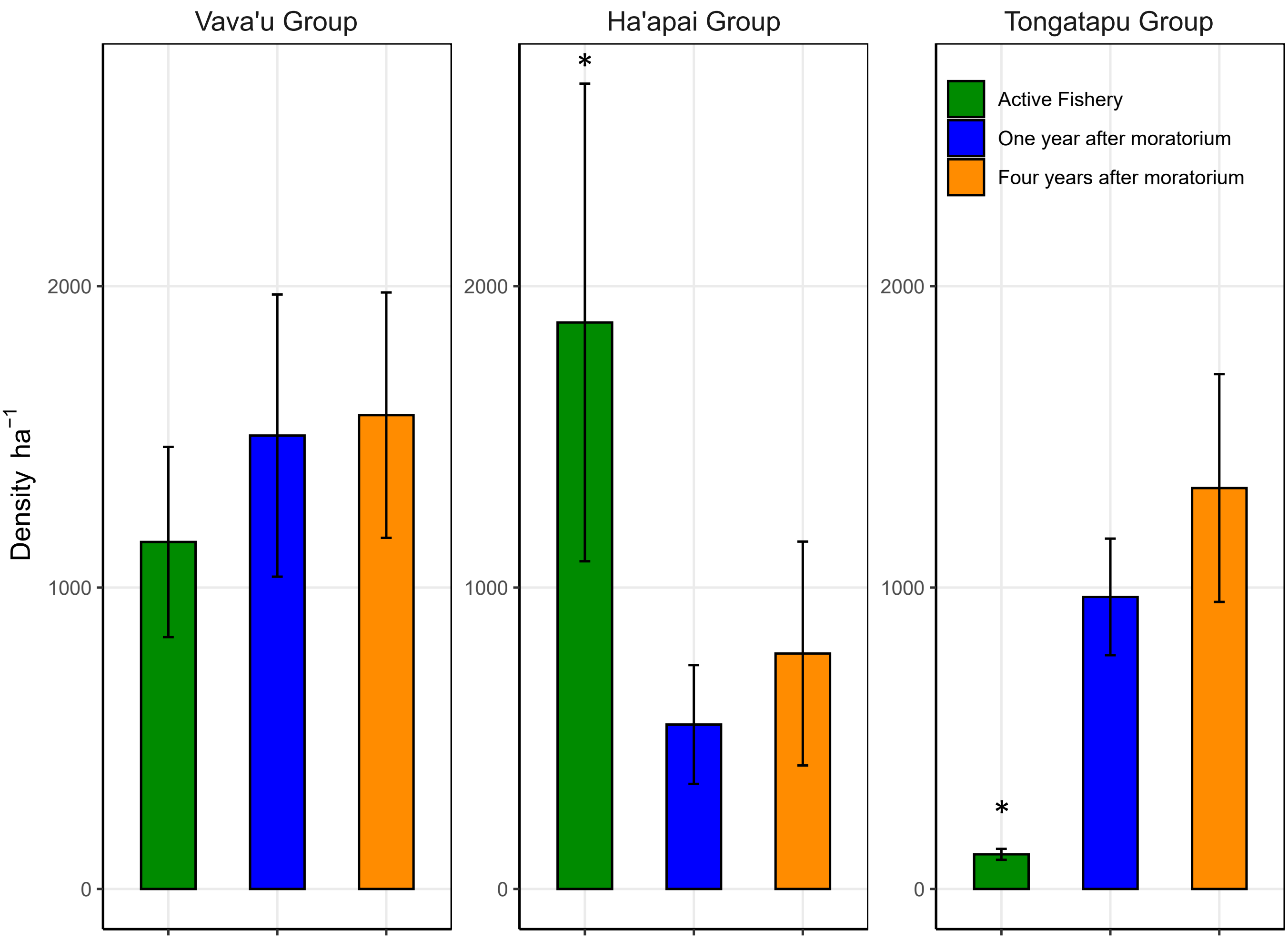


Figure 7. Mean density (± SE) for thirteen sea cucumber species (mokohunu) for each island group across Tonga. (*) indicates significant differences between time periods within each island group ($p < 0.05$).

The density of all high, medium and low value species across the three main island groups remained significantly below their reference density thresholds, with few species showing signs of recovery (Figure 8). Those species that did show some evidence of increasing in density in 2019 compared with other years did not do so consistently across all three island groups. While increases were not significant, there was nevertheless a general trend of increasing abundance for three high value species, *Holothuria whitmaei, H. fuscogilva* and *H. lessoni* in Vava'u, (Figure 8), but not at Ha'apai or Tongatapu (Figure 8). However, these species densities remain approximately three times and ten times below their respective threshold densities for *H. whitmaei*, and for *H. fuscogilva* and *H lessoni* respectively. Few medium value species increased in density after four years' protection to 2019. Increases were limited to *Bohadschia argus* and *Thelenota ananas* in Vava'u island group (Figure 8), and *Stichopus horrens* in both Ha'apai and Tongatapu islands groups.

The density of the low value species *Thelenota anax* and *Holothuria edulis* increased in Vava'u and Ha'apai islands groups respectively, and the density of *Holothuria atra* has shown some recovery in Tongatapu island group; however, this species remains significantly below their reference density.

Historical density comparisons

The mean density in 2019 of common high and medium value species from earlier comparable studies were below historical records (Table 4). Data from 2004, seven years after the initial moratorium, show that the density of sea cucumbers was on average twice as high as in 2019. Notably, the densities of white and black teatfish currently range from 10% to 20% of those found in 1990. In contrast, amberfish appear to be at levels consistent with those observed in 1990 and also appear to have increased threefold since 2015.

*Table 4. Mean density (individuals ha^{-1}) of common sea cucumber species across Ha'apai, Tonga, from 1990 to 2019. * denotes shallow sites, ** denotes deep sites for the 2004 survey. Bold text indicate when densities were higher in 2019 than just before the first moratorium in 1996*

Tongan name	Common name	Scientific name	1990[2]	1996[3]	2004[4]	2016[5,6]	2019[6]
Huhuvalu 'uli'uli	Black teatfish	*Holothuria whitmaei*	4.56 ± 1.43	1.33 ± 0.74	1.10 ± 0.14* 2.71 ± 0.73**	0.17 ± 0.09	1.24 ± 0.4
Huhuvalu hinehina	White teatfish	*Holothuria fuscogilva*	8.6 ± 2.21	2.23 ± 1.12	9.48 ± 1.21**	0.31 ± 0.11	1.66 ± 0.61
Mula	Brown sandfish	*Bohadschia vitiensis*		6.69 ± 5.83	34.01 ± 9.35* 1.35 ± 0.65**	1.70 ± 0.16	1.54 ± 0.21
Elefanite	Elephant trunkfish	*Holothuria fuscopunctata*	6.35 ± 2.59	8.48 ± 2.87	2.22 ± 0.23* 6.25 ± 1.32**	2.16 ± 0.53	3.77 ± 0.94
Pulukalia	Prickly redfish	*Thelenota ananas*	2.97 ± 1.17	0.44 ± 0.44	3.92 ± 0.32* 1.25 ± 0.44**	0.82 ± 0.36	2.33 ± 0.92
Saieniti	Amberfish	*Thelenota anax*	13.34 ± 5.66	3.57 ± 1.55	4.13 ± 0.35* 14.89 ± 1.4**	2.59 ± 0.68	**9.2 ± 2.71**

2 SPC (45 × 5 min swim searches, area estimates from flowmeter available; (Preston and Lokani 1990).
3 Fishery just before closure, SPC (100 m transects using fishing line, 4 m each side of the line;(Lokani et al. 1996).
4 SPC manta tow deep water (top mean) and lagoon transects (bottom mean) (each transect 300 × 2) (Friedman et al. 2011).
5 SPC Sea Cucumber Day Searches (timed swim with 5 m belt transect width) (Moore et al. 2017)
6 SPC reef benthos transect (six 40 m × 2 m belt transect at each station)

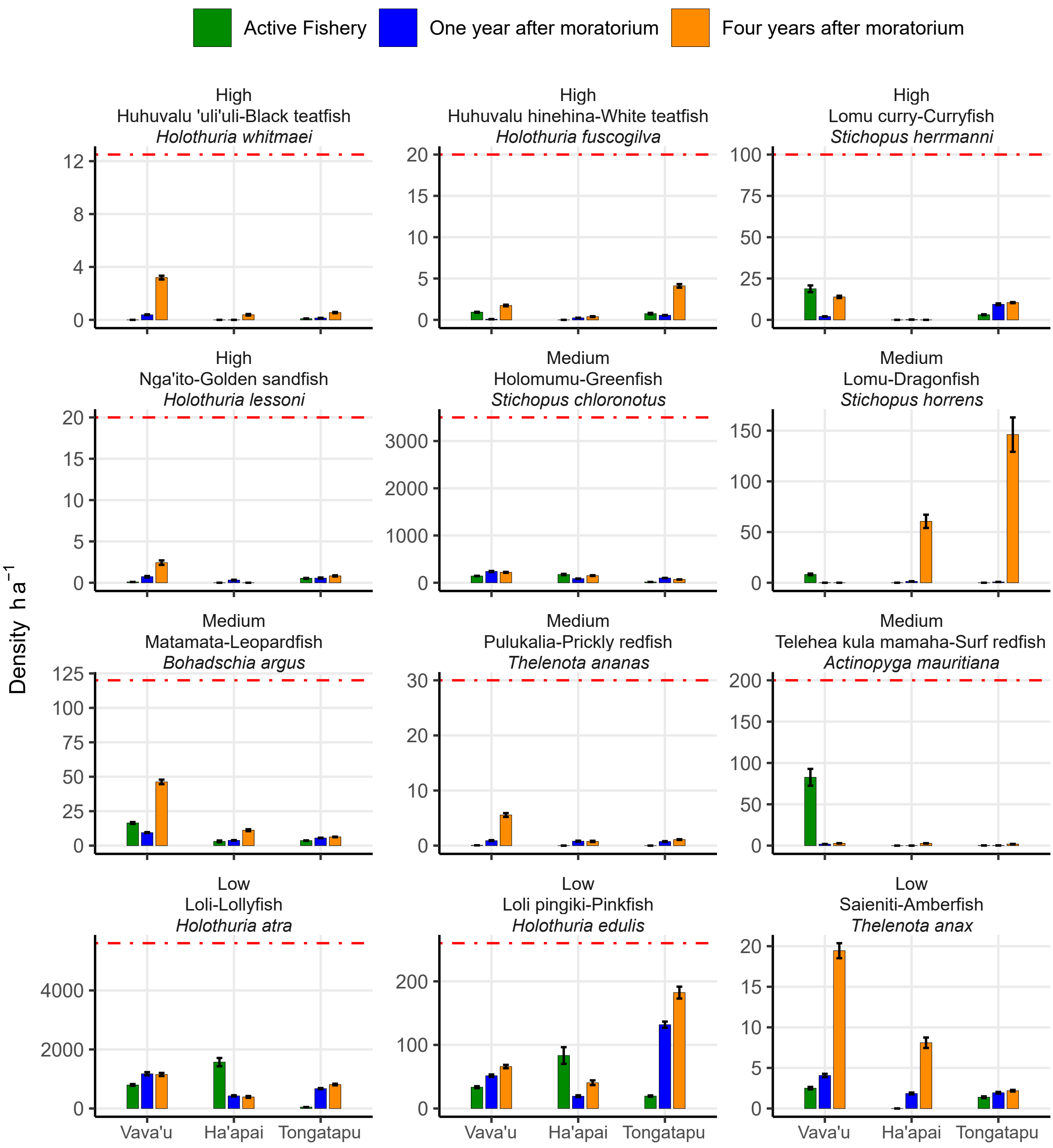


Figure 8. Mean density ha^{-1}, (± SE) for key sea cucumber (mokohunu) species within the Vava'u, Ha'apai and Tongatapu Groups; Plot titles, High, Medium, or Low indicate the commercial value of mokohunu sold on international markets (Purcell et al. 2017), followed by Tongan name, English common name and scientific name respectively; red dashed line indicates regional reference density thresholds for healthy populations sourced from Pakoa et al. (2014), excluding black teatfish, which was sourced from Kinch et al. (2008) and golden sandfish which was set at 20 individuals per hectare using RBT survey methods.

Length

Of the 19 species observed in 2019, only eight species were at densities high enough to make meaningful length–frequency comparisons. However, data for the high value white teatfish, black teatfish and golden sandfish are displayed for reference.

The length–frequency histogram shows an increasing proportion of smaller individuals for low (pinkfish and lollyfish) and medium value (leopardfish) species (Figure 9). The length distributions of lollyfish and leopardfish were larger in the years before 2016 (Figure 9). From 2016 onwards, these same larger individuals between 400 mm and 600 mm were absent. The length–frequency distributions of all other species were similar across surveyed years.

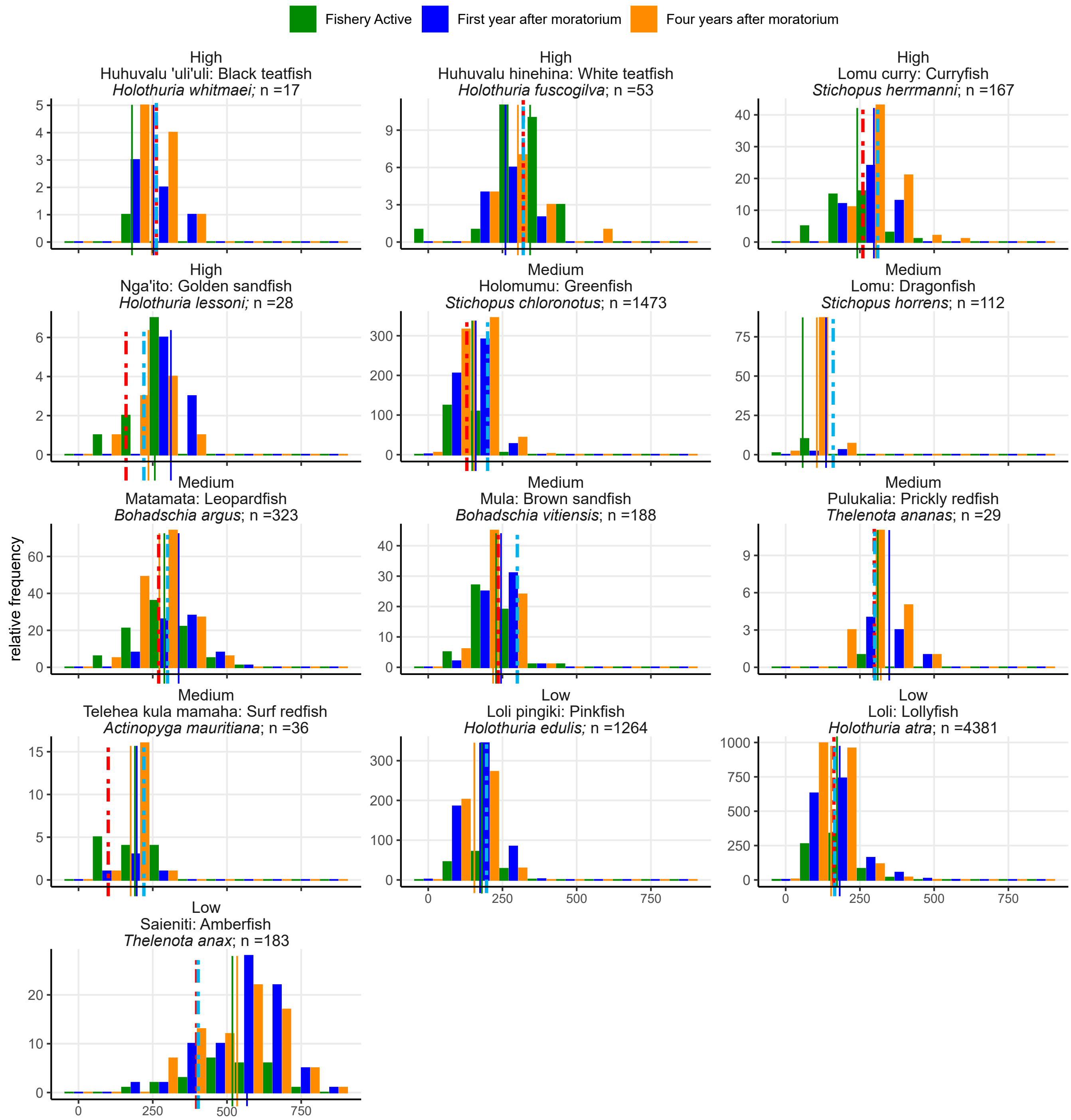


Figure 9. Length frequency for 13 sea cucumber species pooled across Vava'u, Ha'apai, and Tongatapu Groups. Survey years before 2016 during commercial harvests were grouped; coloured solid lines indicate mean length for each period, red dashed line indicates minimum legal live length (pers. comm. Siola'a Malimali.), and blue dashed line indicates length at first maturity (Conand 1990; Conand and Byrne 1993; Purcell et al. 2012). Plot titles: High, Medium, or Low indicate the commercial value of bêche-de-mer (processed sea cucumber) sold on international markets (Purcell et al. 2017); followed by Tongan name, English common name, and scientific name, and (n) represents the total number of length measurements for each species.

Discussion

Results of the 2019 surveys clearly indicate that sea cucumber stocks remain depleted after three and a half years of a moratorium on exports, highlighting that insufficient time has passed to enable species to recover. Friedman et al. (2004) showed that seven years after the first moratorium on exports, density of commercially important species, apart from black teatfish, increased sufficiently to support a small-scale fishery. Prior to the first moratorium, the fishery had been operating from 1984 to 1997, but only became commercially large-scale in the early 1990s when fishing pressure on high and medium value species was intensive. Another survey in 2009, twelve years after the moratorium, showed that five indicator species, again with the exception of black teatfish, had recovered to pre-harvest 1990 levels; these included white teatfish, prickly redfish, amberfish, elephant trunkfish and curryfish (Friedman et al. 2009). In contrast, this survey found relatively few species that were on an upward trajectory, and those that did show some minor recovery were limited to low value lollyfish, pinkfish and medium value amberfish, leopardfish, and dragon fish. Moreover, observations of increases in 2019 are minor and confined to very few stations within each of the three major island groups.

Sea cucumber stocks, given their current levels, will need to remain closed until at least 2025 due to the unprecedented fishing pressure from 2009 to 2014. At the time of their publication, Pakoa et al. (2013) explained that Tonga had gone through two "boom and bust" cycles, with the first boom in exports peaking at 80 tonnes in 1988 and 61 tonnes in 1995 before the introduction of the first moratorium in 1997. Tonga later experienced a much higher export period in 2009 and 2010, with exports of 370 and 312 tonnes respectively. Exports then declined in 2011 to 79 tonnes (Pakoa 2013). In 2014 exports again boomed to 146 tonnes, making it the third boom period before the fishery was again closed in 2015. Relatively smaller harvests between 1989 and 1997 provided respite for many species populations, which allowed them to continue to provide recruits and, during the 10-year moratorium when the fishery was closed, standing stocks were able to rebuild. Pakoa et al. (2013) link the high exports in 2009 and 2010 with previous strong stock recovery. However, it is more likely that most export species consisted of a mix of high, medium and low value species, such as snakefish, pinkfish and lollyfish, which were degrees of magnitude higher in density, and were of no commercial interest in the first 15 years of the fishery. The 2008 harvest season was relatively small with only 15 tonnes harvested from a quota of 189 tonnes, due to the fishery being open for only a relatively short season. Pakoa et al. (2013) highlighted the lack of knowledge about the open season, and licensed operators targeting mainly high value species in Ha'apai, as the reason for the low export volumes. An increase in the number of licenses issued in 2009 resulted in the allocated quota being exceeded by 156 tonnes, and again by 106 tonnes in 2010 (Pakoa et al. 2013). In 2011, the Ministry of Fisheries reduced the export quota to 100 tonnes. Declining exports were later observed, despite extending the open season by two weeks. In 2014, exports were measured at 142 tonnes, again 42 tonnes above the allocated quota. From 1987 to 1997, an 11-year period, a total of 691 tonnes were exported and these consisted primarily of high and medium value species, whereas in the period from 2008 to 2015, an 8-year period, exports were 1.6 times higher, at 1043 tonnes, and consisted of all commercially viable species. The fishing pressure during these later years has had a severe effect on standing stock, as seen in this survey, and specifically on the density of reproductively active adults, ultimately requiring additional time for stock recovery. Hence the recovery rates observed by Friedman et al. (2009) may not apply to the present day fishery, and continued fishery-independent stock assessment is essential to highlight areas of significant recovery and the length of time required for recovery to occur.

Length frequency is a foundational, yet powerful, metric for describing the age structure of populations in many fisheries (Gallucci et al. 1995). For example, the absence of larger individuals suggests heavy fishing pressure (Mmbaga 2013), as these larger individuals are usually of high value and are preferentially selected, while an absence of smaller individuals suggests a lack of recruitment to a population. Tracking the relative abundance of length cohorts through time allows interpretation of whether remnant adults have reproduced sufficiently to supply recruits, which is especially important in heavily fished populations where fertilisation and recruitment success is dependent on the density of breeding adults (Shepherd and Partington 1995). In the early stages of stock recovery, sea cucumber populations may be characterised by an increase in abundance of smaller sized individuals, either through sexual or asexual (fission) reproduction (Ramofafia et al. 2000; Shepherd and Partington 1995). Some species of sea cucumber (e.g. dragonfish, lollyfish, and see Dolmatov (2014) for a review) undergo fission, but the effect on overall density and stock recovery is not well understood. There are examples where stock replenishment programmes have been attempted by artificially inducing fission, although the success of these attempts to influence stock recovery and the time required are uncertain (Battaglene and Bell 2004). Hence, stock recovery via fertilisation, settlement, and recruitment from standing stock of adults is considered the main source of juveniles within Tonga's sea cucumber populations.

Currently in Tonga the data suggest that recruitment to some populations is occurring, yet is limited to low value species such as lollyfish and pinkfish. High value species such as white teatfish, black teatfish and golden sandfish are at such low densities that detection of juveniles was limited or absent. Furthermore, the proportion of individuals greater than length at maturity (L_{50}) for these high value species was relatively low, which further inhibits the likelihood of successful fertilisation, recruitment, and population recovery. During the open season between 2008 and 2015, the minimum legal length was also on or below L_{50}, for golden sandfish and curryfish, for example, and in some cases during the early years of the fishery, there were no size limits, which would have severely affected the density of breeding individuals. MoF is currently revising the minimum legal harvest lengths, which are above the length at first maturity (pers. comm. Siola'a Malimali). Having size limits above length at first maturity (e.g. L_{50} + 20%) is important, especially in heavily fished fisheries such as the sea cucumber fishery, where retention of breeding adults is difficult when quotas have consistently been exceeded. The introduction of revised size limits will allow retention of a proportion of breeding adults in these heavily exploited populations, which will facilitate juvenile replenishment and population maintenance. Given that the market value of sea cucumber is often positively correlated with length (Purcell 2014), introducing minimum harvest length above L_{50} would also help to maximise economic benefits to the community and sustainable use of the fishery over the medium to long term.

It is recognised that the Tonga sea cucumber fishery is currently under a moratorium; however, it is recommended that upon population recovery, and the eventual lifting of the moratorium, management strategies using size limits will need to be augmented with other management measures such as bag limits, quotas, lengthened seasonal/temporal closures, as well as the introduction of a list of permissible species, whereby the list can be based on whether the species' population has recovered sufficiently. The list can also be seasonally adjusted, depending on the level of extraction (e.g. catch per unit effort (CPUE)) and the effect of catch volumes on standing stock. For a review of the potential broad-scale harvest strategies for sea cucumbers in Tonga, and key questions to address for management, please refer to the previous SPC report by Moore et al. (2017).

It was expected that some changes would have been observed in this fishery three and a half years after the moratorium was implemented. However, as little change has occurred in the status of standing stock compared with that published in Moore et al. (2017), and with the exception of the recommendation to extend the moratorium beyond five years up to a minimum of 10 years, the management recommendations published previously remain valid (Moore et al. 2017; Purcell et al. 2009).

References

Abdo D., Coleman G., Ninio R., Osborne K., 2004. Surveys of benthic reef communities using underwater video - Long term monitoring of the Great Barrier Reef - Standard Operating Procedure Number 2.

Allee W.C., 1938. The social life of animals. W W Norton & Co, New York, NY, US. https://doi.org/10.5962/bhl.title.7226

Anderson S.C., 2010. Trends, drivers, and ecosystem effects of expanding global invertebrate fisheries.

Battaglene S.C., Bell J., 2004. The restocking of sea cucumbers in the Pacific Islands, in: Fishery Technical Paper. pp. 109–132.

Charan-Dixon H., 2016. Sea cucumber fisheries in the Kingdom of Tonga: regeneration biology, ecology, and environmental chemistry.

Charan-Dixon H., Goldstien S.J., Vanderhaven B.J., Halafihi T., Tuiano T.L., Gaw S., Glover C.N., 2019. Effects of traditional fishing techniques on internal organ regeneration, physiology, and biochemistry in the tropical sea cucumber Stichopus horrens. Journal of Experimental Marine Biology and Ecology 510:15–22. https://doi.org/10.1016/j.jembe.2018.09.007

Dolmatov I.Y., 2014. Asexual Reproduction in Holothurians [WWW Document]. The Scientific World Journal. https://doi.org/10.1155/2014/527234

Friedman K., Eriksson H., Tardy E., Pakoa K., 2011. Management of sea cucumber stocks: patterns of vulnerability and recovery of sea cucumber stocks impacted by fishing. Fish and Fisheries 12:75–93. https://doi.org/10.1111/j.1467-2979.2010.00384.x

Friedman K., Lokani P., Fale P., Mailau S., Ramohia P., Ramofafia C., 2004. Survey of the Sea Cucumber Resources Of Ha'apai, Tonga 38.

Friedman K.J., Secretariat of the Pacific Community, Coastal Fisheries Programme, 2009. Tonga country report: profiles and results from survey work at Ha'atafu, Manuka, Koulo and Lofanga. Secretariat of the Pacific Community, Coastal Fisheries Programme, Noumea, New Caledonia.

Gallucci V.F., Saila S.B., Gustafson D.J., Rothschild B.J., 1995. Stock Assessment: Quantitative methods and applications for small scale fisheries. CRC Press.

Kinch J., Purcell S., Uthicke S., Friedman K., 2008. Population status, fisheries and trade of sea cucumbers in the Western Central Pacific, in: Sea Cucumbers: A Global Review of Fisheries and Trade, FAO Fisheries and Aquaculture Technical Paper. p. 51.

Lawrence J.M., Herrera J., 2000. Stress and Deviant Reproduction in Echinoderms. Zoological Studies 21.

Lokani P., Matoto S.V., Ledua E., 1996. Survey of Sea Cucumber Resources At Ha'apai, Tonga, May/June 1996 14.

MacTavish T., Stenton-Dozey J., Vopel K., Savage C., 2012. Deposit-feeding sea cucumbers enhance mineralization and nutrient cycling in organically-enriched coastal sediments. PloS one 7.

Michio K., Kengo K., Yasunori K., Hitoshi M., Takayuki Y., Hideaki Y., Hiroshi S., 2003. Effects of deposit feeder Stichopus japonicus on algal bloom and organic matter contents of bottom sediments of the enclosed sea. Marine Pollution Bulletin 47:118–125.

Mmbaga T.K., 2013. The effect of fishing on the ecology of sea cucumbers (Holothuroidea: Echinodermata) Holothuria scabra and Holothuria nobilis in Tanzanian sea water. International Journal of Development and Sustainability 2:1099–1126.

Moore B., Bosserelle P., Mailau S., Siaosi V., Siaosi F., Havea T., Malimali S., 2017. The status of sea cucumbers in the Kingdom of Tonga in 2016. Pacific Community, Noumea.

Ogle D.H., 2016. Introductory Fisheries Analyses with R 327.

Pakoa K., Friedman K.J., Moore B., Tardy E., Bertram I., Secretariat of the Pacific Community, Coastal Fisheries Programme, 2014. Assessing tropical marine invertebrates: a manual for Pacific Island resource managers.

Pakoa K.M., Ngaluafe P.V., Lotoahea T., Matoto S.V., Bertram I., 2013. The status of Tonga's sea cucumber fishery, including an update on Vava'u and Tongatapu 47.

Pinheiro J., Bates D., DebRoy S., Sarkar D., 2019. R Core Team. 2019. nlme: linear and nonlinear mixed effects models. R package version 3.1-141.

Preston G.L., Lokani P., 1990. Report of a survey of the sea cucumber resources of Ha'apai, Tonga (No. 1). South Pacific Commission, Noumea, New Caledonia.

Purcell S.W., Conand C., Uthicke S., Byrne M., 2016. Ecological roles of exploited sea cucumbers. Oceanography and Marine Biology 54:367–386.

Purcell S.W., Crona B.I., Lalavanua W., Eriksson H., 2017. Distribution of economic returns in small-scale fisheries for international markets: A value-chain analysis. Marine Policy 86:9–16. https://doi.org/10.1016/j.marpol.2017.09.001

Purcell S.W., Gossuin H., Agudo N.S., 2009. Status and management of the sea cucumber fishery of La Grande Terre, New Caledonia. WorldFish.

Purcell S.W., Mercier A., Conand C., Hamel J.-F., Toral-Granda M.V., Lovatelli A., Uthicke S., 2013. Sea cucumber fisheries: global analysis of stocks, management measures and drivers of overfishing [WWW Document]. Fish and Fisheries. https://doi.org/10.1111/j.1467-2979.2011.00443.x

R Core Team, 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing [WWW Document]. URL https://www.R-project.org/ (accessed 4.29.16).

Ramofafia C., Battaglene S.C., Bell J.D., Byrne M., 2000. Reproductive biology of the commercial sea cucumber Holothuria fuscogilva in the Solomon Islands. Marine Biology 136:1045–1056.

Salcone J., Tupou-Taufa S., Brander L., Fernandes L., Fonua E., Matoto L., Leport G., Pascal N., Seidi A., Tu'iva L., Wendy H., 2015. National marine ecosystem service valuation: Tonga. MACBIO (GIZ/ IUCN/ SPREP).

Sekhon J.S., 2008. Multivariate and propensity score matching software with automated balance optimization: the matching package for R. Journal of Statistical Software, Forthcoming.

Sewell M.A., 1990. Aspects of the ecology of Stichopus mollis (Echinodermata: Holothuroidea) in north-eastern New Zealand. New Zealand Journal of Marine and Freshwater Research 24:97–103.

Shepherd S., Partington D., 1995. Studies on southern Australian abalone (Genus Haliotis), 16. Recruitment, habitat and stock relations. Mar. Freshwater Res. 46:669. https://doi.org/10.1071/MF9950669

Sloan N.A., 1984. Echinorderm fisheries of the world: a review. Echinodermata (Proceedings of the Fifth International Echinoderm Conference), (Proceedings of the Fifth International Echinoderm Conference). AA Balkema Publishers, Rotterdam, Netherlands.

Toral-Granda V., Lovatelli A., Vasconcellos M., Food and Agriculture Organization of the United Nations (Eds.), 2008. Sea cucumbers: a global review of fisheries and trade, FAO fisheries and aquaculture technical paper. Food and Agriculture Organization of the United Nations, Rome.

Appendices

Appendix 1: Statistical analysis

Table A1. Pairwise t-test results of overall sea cucumber density through time.

contrast	Island	estimate	SE	df	t ratio	*p* value
Exports Open – One year after moratorium	Ha'apai Group	2.06	0.44	506	3.36	**0.002**
Exports Open – Four years after moratorium	Ha'apai Group	1.39	0.30	506	1.54	**0.271**
One year after moratorium – Four years after moratorium	Ha'apai Group	0.68	0.09	506	−2.90	**0.011**
Exports Open – One year after moratorium	Tongatapu Group	0.99	0.15	506	−0.04	0.999
Exports Open – Four years after moratorium	Tongatapu Group	0.85	0.12	506	−1.13	0.493
One year after moratorium – Four years after moratorium	Tongatapu Group	0.85	0.11	506	−1.27	0.413
Exports Open – One year after moratorium	Vava'u Group	0.82	0.11	506	−1.43	0.325
Exports Open – Four years after moratorium	Vava'u Group	0.58	0.08	506	−4.00	**<0.001**
One year after moratorium – Four years after moratorium	Vava'u Group	0.71	0.09	506	−2.67	**0.021**

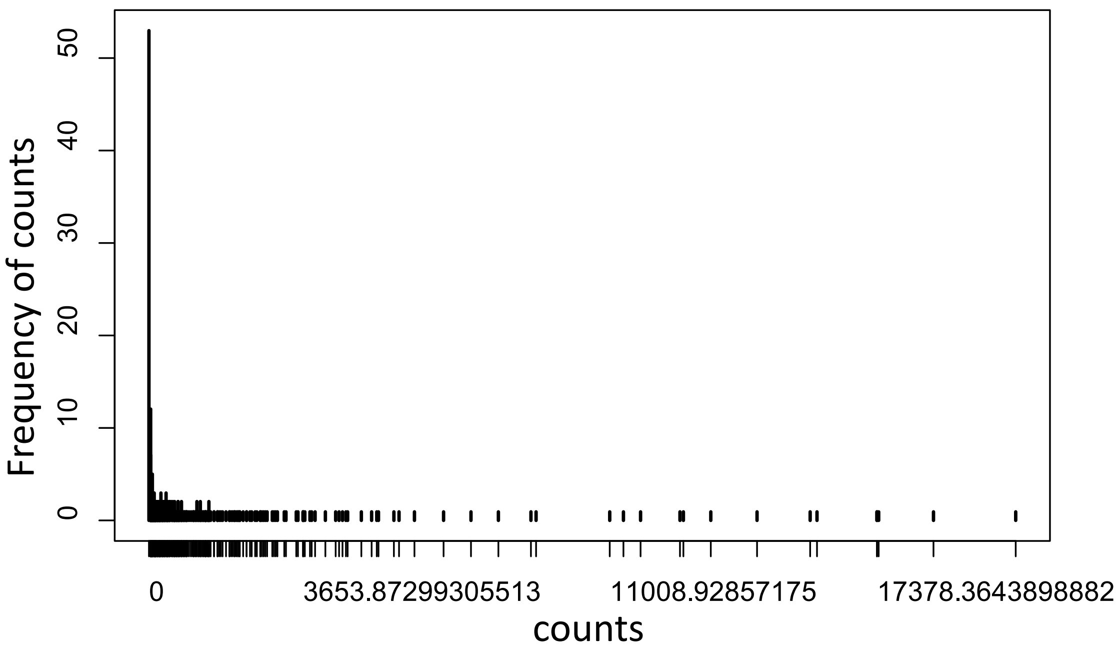


Figure A1. Frequency of occurrence table for the counts of sea cucumbers; the distribution of counts are strongly left skewed, which highlights that zero counts were numerous among the 189 reef benthos transect (RBT) stations.

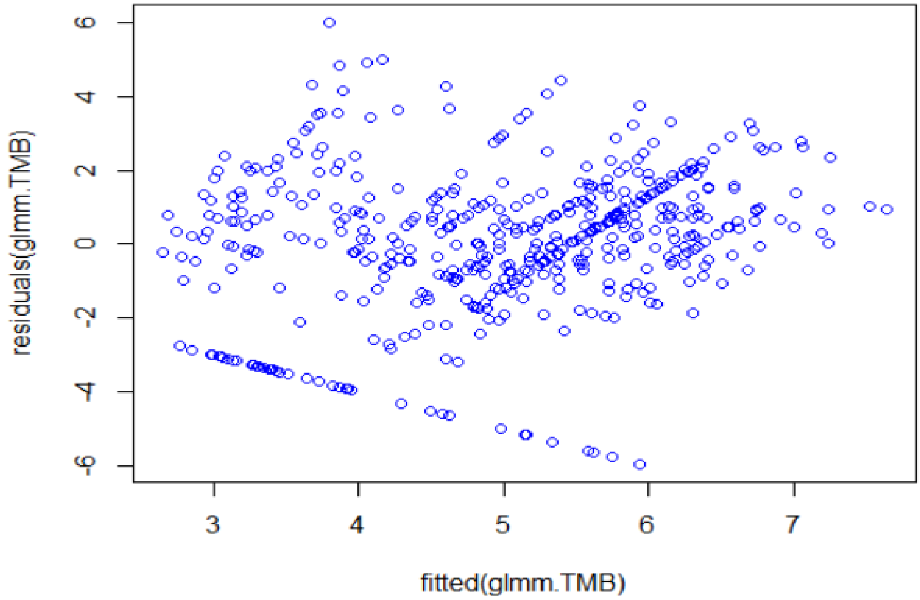


Figure A2. Distribution of residuals in the model before the inclusion of station-level random effects. The strong pattern observed in negative residuals shows random effects have not been accounted for.

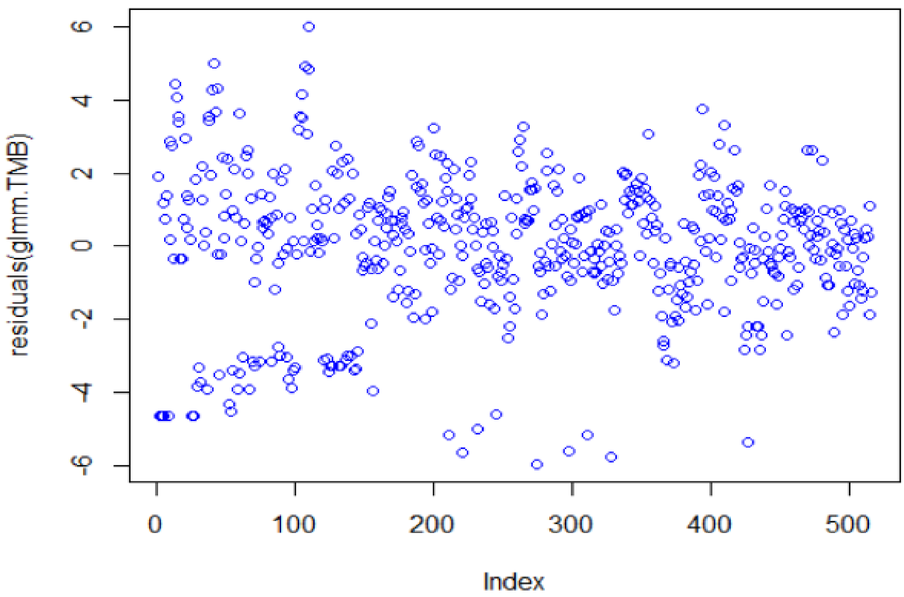


Figure A3. Distribution of residuals in model after the inclusion of station-level random effects. No pattern in negative residuals shows station-level random effects have been accounted for.

Appendix 2: Length distribution tests

Table A2. Results of Kolmogorov–Smirnov length distribution tests for each species between time periods when exports were open and after the initiation of the moratorium in 2015

Scientific name	Tongan name	Common name	value	TSM.FACT1	TSM.FACT2	ks.boot.stat	ks.boot.pvals	ks.pval	p.adjust (Bonferonni)
Actinopyga mauritiana	Telehea kula mamaha	Surf redfish	Medium	Exports Open	First year after moratorium	0.31	0.64	0.88	1.00
Actinopyga mauritiana	Telehea kula mamaha	Surf redfish	Medium	Exports Open	4 years after moratorium	0.41	0.07	0.17	1.00
Actinopyga mauritiana	Telehea kula mamaha	Surf redfish	Medium	First year after moratorium	4 years after moratorium	0.41	0.27	0.52	1.00
Bohadschia argus	Matamata	Leopardfish	Medium	Exports Open	First year after moratorium	0.29	0.00	0.00	0.03
Bohadschia argus	Matamata	Leopardfish	Medium	Exports Open	4 years after moratorium	0.12	0.25	0.39	1.00
Bohadschia argus	Matamata	Leopardfish	Medium	First year after moratorium	4 years after moratorium	0.36	0.00	0.00	0.00
Holothuria atra	Loli	Lolly fish	Low	Exports Open	First year after moratorium	0.06	0.02	0.05	0.67
Holothuria atra	Loli	Lolly fish	Low	Exports Open	4 years after moratorium	0.16	0.00	0.00	0.00
Holothuria atra	Loli	Lolly fish	Low	First year after moratorium	4 years after moratorium	0.14	0.00	0.00	0.00
Holothuria edulis	Loli pingiki	Pink fish	Low	Exports Open	First year after moratorium	0.06	0.58	0.79	1.00
Holothuria edulis	Loli pingiki	Pink fish	Low	Exports Open	4 years after moratorium	0.16	0.00	0.01	0.05
Holothuria edulis	Loli pingiki	Pink fish	Low	First year after moratorium	4 years after moratorium	0.16	0.00	0.00	0.00
Holothuria fuscogilva	Huhuvalu hinehina	White teatfish	High	Exports Open	First year after moratorium	0.67	0.00	0.00	0.01
Holothuria fuscogilva	Huhuvalu hinehina	White teatfish	High	Exports Open	4 years after moratorium	0.52	0.00	0.01	0.09
Holothuria fuscogilva	Huhuvalu hinehina	White teatfish	High	First year after moratorium	4 years after moratorium	0.25	0.56	0.80	1.00
Holothuria lessoni	Nga'ito	Golden sandfish	High	First year after moratorium	4 years after moratorium	0.78	0.00	0.01	0.09
Holothuria whitmaei	Huhuvalu 'uli'uli	Black teatfish	High	First year after moratorium	4 years after moratorium	0.67	0.69	0.84	1.00
Stichopus chloronotus	Holomumu	Green fish	Medium	Exports Open	First year after moratorium	0.14	0.00	0.00	0.07
Stichopus chloronotus	Holomumu	Green fish	Medium	Exports Open	4 years after moratorium	0.08	0.14	0.24	1.00
Stichopus chloronotus	Holomumu	Green fish	Medium	First year after moratorium	4 years after moratorium	0.08	0.02	0.04	0.54
Stichopus horrens	Lomu	Dragon fish	Medium	Exports Open	First year after moratorium	0.80	0.00	0.02	0.12
Stichopus horrens	Lomu	Dragon fish	Medium	Exports Open	4 years after moratorium	0.83	0.00	0.00	0.00
Stichopus horrens	Lomu	Dragon fish	Medium	First year after moratorium	4 years after moratorium	0.53	0.05	0.14	1.00
Thelenota ananas	Pulukalia	Prickly redfish	Medium	Exports Open	First year after moratorium	0.63	0.76	0.88	1.00
Thelenota ananas	Pulukalia	Prickly redfish	Medium	Exports Open	4 years after moratorium	0.55	0.84	0.94	1.00
Thelenota ananas	Pulukalia	Prickly redfish	Medium	First year after moratorium	4 years after moratorium	0.30	0.48	0.68	1.00
Thelenota anax	Saieniti	Amberfish	Low	Exports Open	First year after moratorium	0.24	0.13	0.22	1.00
Thelenota anax	Saieniti	Amberfish	Low	Exports Open	4 years after moratorium	0.11	0.86	0.97	1.00
Thelenota anax	Saieniti	Amberfish	Low	First year after moratorium	4 years after moratorium	0.20	0.06	0.10	1.00

Pacific Community
Communauté du Pacifique

BP D5 • 98848 NOUMEA CEDEX
NEW CALEDONIA

Telephone: +687 26 20 00
Facsimile: +687 26 38 18
Email: cfpinfo@spc.int

BP D5 • 98848 NOUMÉA CEDEX
NOUVELLE-CALÉDONIE

Téléphone : +687 26 20 00
Télécopieur : +687 26 38 18
Courriel : cfpinfo@spc.int

ISBN 978-982-00-1280-6