A Preliminary Evaluation of a Recently Enacted Reef-Fish Management Plan at Kamiali Wildlife Management Area, Papua New Guinea

Ken Longenecker, Ross Langston, and Holly Bolick

Honolulu, Hawaii
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COVER

An aerial view of the fringing reef on north side of Cape Dinga, Kamiali Wildlife Management Area. The reef is protected as part of the reef-fish management plan being evaluated in this report. The point of land is the approximate boundary between two levels of protection. No fishing is allowed on the reef in the foreground. *Derris* (poison rope, or rotenone) fishing is prohibited on the reef in the background. Photo: Ross Langston.

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EXECUTIVE SUMMARY

The Kamiali Initiative is a Bishop-Museum-led project to develop a self-sustaining cycle of environmental conservation, scientific research, and economic development in the coastal community of Kamiali, Papua New Guinea. The area includes approximately 120,000 acres of terrestrial and marine habitat, and is larger than the land area of 16 countries. The success of the Kamiali Initiative is contingent upon ~ 600 Kamiali residents preserving the natural environment such that biological field researchers are motivated to work in the area. This project is arguably the most successful and is the only fully sustainable large-scale terrestrial/marine biodiversity conservation project in Papua New Guinea.

The most-challenging conservation issues at Kamiali center on coral-reef fishes. Fish are the source of the overwhelming majority of dietary protein for this coastal village, and coral-reefs are preferred fishing sites. To be successful, conservation practices must balance the conflicting needs of protecting fish populations against the cultural value of and dietary need for subsistence fishing.

In 2014, Kamiali residents crafted and enacted a reef-fish management plan. The goal of that management plan is to promote sustainable fishing on coral reefs at Kamiali Wildlife Management Area (KWMA) and thus provide residents with current needs (food), attract current income (derived from marine research), and to prevent the long-term decline in exploited fish populations such that future generations can obtain adequate food and income.

The purpose of this report is to conduct a preliminary evaluation of the management plan one year after its enactment. Here we describe the post-plan status of Kamiali's exploited reef-fish populations and compare the results to baseline data collected for a period of six years before the plan was enacted.

Our data sets were robust enough for statistical analysis of 18 species. Of these, nine species (50%) were significantly longer, and there was no significant difference in average length for seven species one year after the plan was enacted. Thus, 89% of species were the same size or larger post-plan. Average weight increased by 46.2%, the percent of reproductively sized individuals increased 14%, and the percent of mature females increased 11%.

These results suggest that the management plan had a desirable effect on KWMA's reef-fish resources, that current residents will be able to more-easily meet their dietary and economic needs, and that post-plan fish populations will be more likely to be able to "seed" future generations of fish and thus provide for the needs of future generations of KWMA residents. We strongly recommend additional monitoring to build more-robust data sets (and permit more-robust analysis) before KWMA's reef-fish management plan is promoted elsewhere. In the meantime, we suggest that KWMA residents continue adhering to the plan.

INTRODUCTION

This report presents the results of research focused on the size structure of select exploited reef fishes at Kamiali Wildlife Management Area (KWMA), Morobe Province, Papua New Guinea in 2015. Those results are compared to six years of baseline data (Longenecker *et al*. 2009, 2010, 2011, 2012, 2013a, 2014a) to evaluate a reef-fish management plan crafted and enacted by KWMA residents in 2014.

General Background

Kamiali residents, who hold title to their territory and traditional tenure over their natural resources, established the KWMA in 1996. It contains 32,000 hectares of terrestrial habitat and 15,000 hectares of adjacent marine habitat. KWMA is remote, located about 65 kilometers south of the port town of Lae. There are no roads to (or in) the village. Its approximately 600 residents obtain most of life's needs from the surrounding environment.

Gardening and subsistence fishing are the economic basis throughout much of coastal Papua New Guinea (PNG) and are a focus of life in many villages; however, residents need money for basic supplies and services (*e.g.*, medicine, education, and clothing). These needs, combined with a lack of income, have made exploitation of natural resources (*e.g.*, logging, mining) a tempting short-term source of money elsewhere in PNG. However, logging and mining in PNG often result in disastrous long-term environmental and social impacts.

In the interest of conserving their natural resources, and thus preserving their traditional lifestyle, Kamiali leaders signed, in 2006, a Memorandum of Understanding with Bishop Museum outlining the development of a world-class remote scientific research station at KWMA. Visiting researchers pay fees for research permits, field assistance, lodging, and meals. This revenue helps fund educational costs and community-development projects. The Kamiali Initiative thus creates a link between economic benefit and environmental conservation, and provides a strong incentive for villagers to protect their land and water in perpetuity (Figure 1).

Fishing for coral-reef species may be the biggest challenge to the Kamiali Initiative; marine fishes provide the vast majority of dietary protein for this coastal village, and coral reefs are preferred fishing sites. For the conservation-research-income cycle to work in Kamiali waters, the village must balance marine conservation with the need for and cultural value of exploiting the marine habitat.

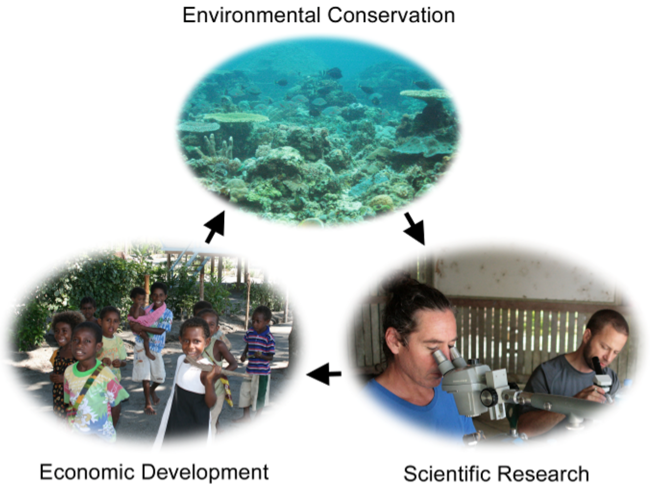


Figure 1. Conceptual model of the Kamiali Initiative: A well-managed environment attracts biological research, providing a means of economic development to pay for school and medicine, thus providing incentive for continued environmental conservation.

Reef-Fish Management Plan

In an effort to balance conservation and exploitation, Kamiali residents crafted and enacted a reef-fish management plan in 2014 (Longenecker *et al*. 2014b). The end goal of this management plan is to promote sustainable fishing, defined here as harvesting fish in a manner that does not result in their long-term decline, thereby maintaining the potential for fish populations to meet the needs of future generations.

The KWMA community should benefit from sustainable fishing practices because well-managed reef-fish populations will allow the village to meet its current needs (obtain food), increase the current economic value of its reefs (attract marine research by leaving more live fish on the reef), and meet the food needs and economic aspirations of future generations.

The plan focuses on one of the most-easily understood concepts in fishery management and conservation: harvest fish only after they have grown large enough to reproduce. This approach allows living fish to "seed" the next generation (Froese 2004).

The plan also recognizes that fish are the primary source of dietary protein for KWMA residents, and that obtaining adequate nutrition must be a priority in this subsistence community. Therefore, the plan explicitly states that *no person should go hungry or risk malnutrition in the interest of adhering to the plan*.

To promote an increase the percentage of adult-sized fish in the catch at KWMA, the plan:

- Presents current knowledge about the reproductive size of heavily exploited species.
- Encourages the release of viable immature fish.
- Encourages residents to use their knowledge of fish and fishing to choose techniques and locations likely to yield adult-sized fish.

The plan also incorporates spatial refuge to limit fishing pressure, while acknowledging the cultural value of the often controversial practice of fish poisoning (*i.e.*, fishing with *Derris* root, known locally as poison rope). Since pre-history, poisoning fish with crushed or ground plant parts – usually *Derris* root – has been a traditional fishing method used by indigenous cultures throughout the tropics (Stokes 1922, Williams 1938, Gatty 1947, Krumholz 1948, Meadows 1973, Galzin 1979, Bishop *et al*. 1982, Allen 1986, Masse 1986, Eldredge 1987). *Derris* fishing will usually result in a large catch, and is useful when preparing for feasts or during periods of starvation. However, *Derris* fishing is non-selective; it will kill all fish, large or small, in the area where *Derris* root is applied. If this fishing method is used too often, KWMA residents risk killing too many immature fish and, ultimately, population-level reproductive failure of their food fishes.

To reduce the chance that traditional fish-poisoning will cause major declines in their reef-fish populations, KWMA residents chose to include in the plan:

- A buffer, or no-take, zone (Figure 2). All fishing methods are prohibited within the buffer zone. The buffer zone includes the reef area between Aramaua and Puko (7.29861°S, 147.13168°E to 7.29810°S, 147.13942°E).
- A fish-poisoning ban on the reef seaward (east) of the buffer zone (Figure 2). The no-poison zone was established to reduce the chance that water currents will sweep poison into the buffer zone. Other fishing methods may be used in the no-poison zone. Because poisoning is also prohibited within the buffer zone, the total area where traditional fish-poisoning is prohibited covers about 25% of the reef flat at KWMA. The no-poison zone extends from Puko to Dinga (7.29810°S, 147.13942°E to 7.30476°S, 147.15408°E).
- Poison only when a large number of fish are needed (*e.g.*, feasts or when food is scarce).

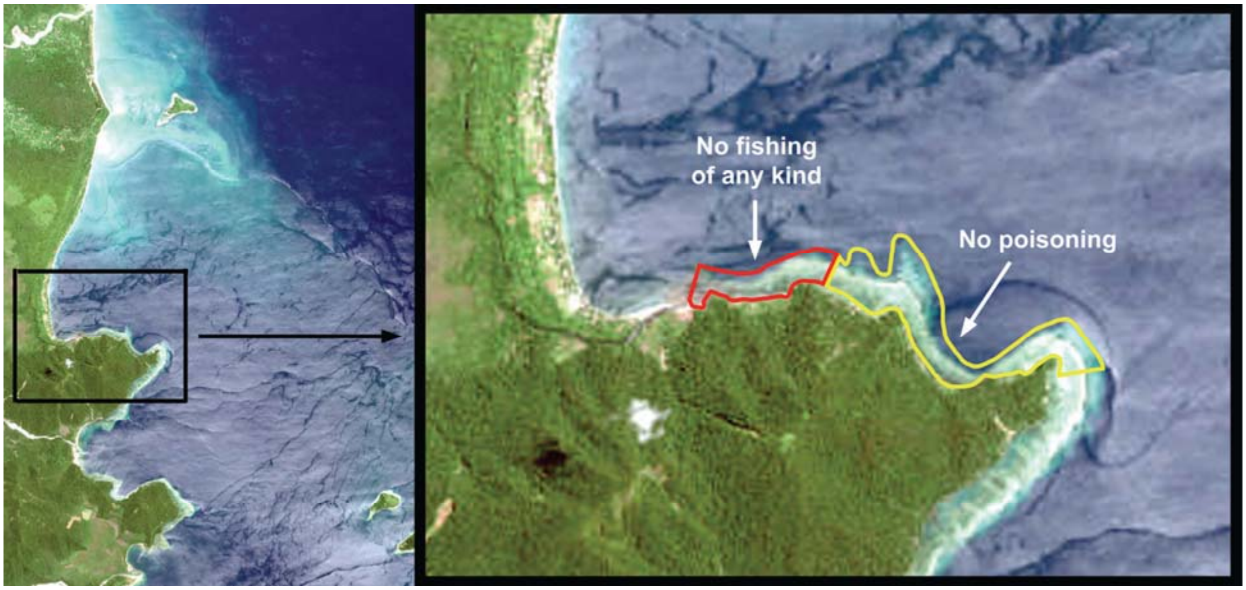


Figure 2. Protected areas at KWMA. The left panel shows the marine area influenced by the reef fish management plan. The right panel shows a close-up of Cape Dinga; the no-take zone is circumscribed in red, *Derris* (or poison-rope) fishing is prohibited in the area circumscribed by yellow (and, by definition, the area circumscribed in red). Satellite image courtesy of the GeoEye Foundation.

Purpose

KWMA's reef-fish management plan may serve as a model for the sustainable use of coral-reef fishes by subsistence communities in the Indo-Pacific region. However, before adopting the plan elsewhere, and to avoid perpetuating an ineffectual plan at KWMA, it must be critically evaluated. The purpose of this report is to compare the demographic characteristics of exploited reef fishes one year after the reef fish management plan was adopted to baseline data collected for six years before the plan was adopted. Specifically, we evaluate whether desirable changes in reef-fish populations occurred after the plan was established.

Desirable demographic characteristics would be average fish size remaining the same or increasing through time *and* average fish size being equal to or larger than adult size. Given the assumption that people generally prefer to catch larger fish, stable or increasing average fish length would suggest that fishing activities are not greatly reducing the number of large fish at KWMA. An average size equal to or greater than adult size would suggest that there are enough reproductive individuals to "seed" the next generation.

Here, we conduct a preliminary evaluation of the reef-fish management plan. Increasing average lengths would suggest that the management plan had a positive effect on coral-reef-fish populations at KWMA. No change in average lengths would suggest that fishing at KWMA is sustainable, but would also suggest that the plan had no real impact on reef-fish populations. Decreasing average lengths would suggest that fishing is not sustainable and that another approach to managing coral reef fishes is needed at KWMA.

Kala Pronunciation Guide

To make the information presented in this report more accessible to the people whose lives are influenced by the reef-fish management plan, we present the Kala fish names used by residents of the Kamiali Wildlife Management Area. Kala is the vernacular (or native) language of approximately 2,000 people from six villages along the Huon Coast.

English speakers will recognize most Kala letters. Shared consonants are pronounced the same in both languages; however English speakers may hear the Kala "l" as an English "r". The Kala language has ten vowels. It also has a consonant not used in English. The following pronunciation guide is paraphrased from DeVolder *et al*. 2012:

- a is pronounced "a" as in apple.
- e is pronounced "ay" as in way.
- i is pronounced "ee" as in see.
- o is pronounced "oa" as in boat.
- u is pronounced "oo" as in boot.
- The diacritical mark ~, called a *titi* (meaning wave) in Kala, may appear with any vowel (ã, ẽ, ĩ, õ, ũ) and indicates the vowel is nasalized. That is, air is let into the nasal cavity during pronunciation.
- ŋ is pronounced "ng" as in song.

METHODS

Study Area

Kamiali is one of six Kala-speaking villages in Papua New Guinea and is located on the Huon Coast, approximately 64 km SSE of the port city, Lae. Approximately 600 residents hold title to and control the use of land, adjacent marine water, and the resources contained therein. The northern boundary of the Kamiali Wildlife Management Area (KWMA) is the mouth of the Bitoi River, whereas the Sela River is the southern limit (Figure 3). Nassau and Saschen Bays are wholly contained within the management area, as are Lababia and Jawani Islands and Capes Dinga and Roon. The northern part of Hessen Bay is also contained within the management area.

The terrestrial portion of the KWMA is remarkably undeveloped and characterized by lush vegetation. Kamiali Village is concentrated along the northern portion, where the shoreline is exclusively sandy beach. South of the village, the shoreline is dominated by fringing reefs on Capes Dinga and Roon. Fringing reefs also surround the islands of Lababia and Jawani. These reef flats transition abruptly to a fore reef which is steep, typically descending 20 to 30 meters. At their bases, the reefs give way to sandy sediment that is believed to occupy the majority of the marine area. Some coral outcroppings, patch reefs and pinnacles are interspersed throughout this presumably sedimentary area. The combined horizontal and vertical area (on reef flats and fore reefs, respectively) occupied by coral is approximately 248 ha (Longenecker *et al*. 2015).

Fishery Surveys

From 24 May – 9 June 2015, we conducted 14 laser-videogrammetry surveys to describe the size distribution of exploited reef fishes in Kamiali Wildlife Management Area. We used closed-circuit rebreathers with air diluent as life support to reach depths to 42 m.

Our 2015 dive protocol was a marked departure from that used during baseline surveys when we used 10/50 trimix diluent to reach maximum depths of 94 m. The change was driven by dive-safety considerations after the failure of gas analyzers (*i.e.*, we could not mix diluent accurately enough to work safely at 94 m).

Table 1. List of marine sites surveyed at Kamiali Wildlife Management Area during 2015. Latitude and longitude were estimated by GPS using the WGS84 datum. FR = Fringing Reef, OP = Offshore Pinnacle, PR = Patch Reef.

Survey	Date	Latitude (ºS)	Longitude (ºE)	Habitat	Max Depth (m)
1	24-May-15	7.29838	147.13963	FR	23
2	25-May-15	7.29858	147.13184	FR	34
3	26-May-15	7.31601	147.20465	OP	24
4	28-May-15	7.30760	147.16638	OP	22
5	29-May-15	7.33703	147.14738	FR	24
6	30-May-15	7.32928	147.20532	OP	24
7	01-Jun-15	7.30425	147.15440	FR	42
8	02-Jun-15	7.32938	147.20720	OP	31
9	03-Jun-15	7.32909	147.20520	OP	26
10	04-Jun-15	7.33007	147.20633	OP	26
11	05-Jun-15	7.33845	147.15581	FR	31
12	06-Jun-15	7.34368	147.16580	OP	28
13	08-Jun-15	7.30271	147.15005	FR	27
14	09-Jun-15	7.30849	147.16614	OP	27

We concentrated on the same habitats described during baseline work. Surveys in 2015 focused on offshore pinnacles and fringing reefs (Table 1, Figure 3). Seven surveys were conducted at previously established sites for coral growth monitoring (surveys 1, 4, 6 - 10). The remaining survey sites were randomly selected. Here we superimposed a grid onto a satellite image of KWMA, with each square of the grid representing one hectare. We then numbered each square that included reef crest. We used randomly generated numbers to select a series of squares, and determined the latitude and longitude at the center of each. In the field, we used a global positioning system (GPS) receiver to navigate to the coordinates, and then began our surveys on the nearest reef crest.

To estimate fish lengths, a high-definition video camera fitted with parallel laser pointers was used to capture images of individual fish when they were oriented perpendicular to the laser-beam axes. We used editing software to review the video and capture still frames where both lasers appeared on the fish. Because the beams are parallel, the lasers superimpose a reference scale on the side of the fish, allowing length estimates by solving for equivalent ratios. Our length estimates were calculated using ImageJ software (Rasband 2009). Longenecker & Langston (2008) have demonstrated a nearly 1:1 relationship between estimated and actual fish lengths. Further, a prediction interval suggests 95% of estimates will be within 0.5 cm of the actual fish length (Longenecker & Langston 2008).

The species included in the 2015 fishery survey met the following five criteria: 1) they are reef fishes; 2) exploited by local fishers; 3) common enough to have been captured at least several times on video; 4) can be reliably identified from still images; and 5) were included in the baseline study (Longenecker *et al*. 2014a). A total 79 species met these criteria.

Analysis

We compared average fish lengths from laser-videogrammetry surveys conducted before and after adoption of the reef -fish management plan. Post-plan average lengths were estimated

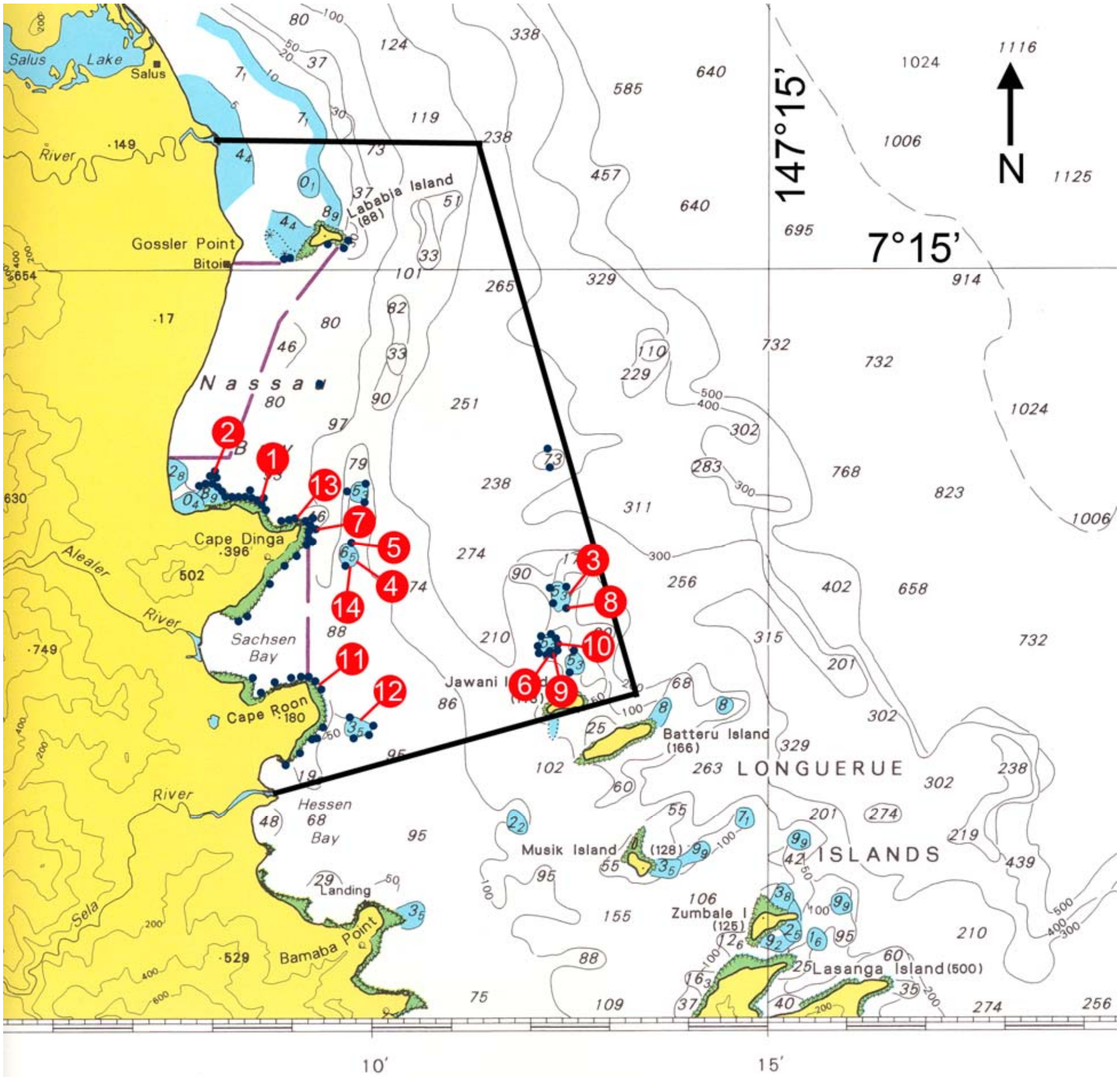


Figure 3. The marine portion of Kamiali Wildlife Management Area (outlined in black). Red circles indicate locations of 2015 survey sites (coordinates are given in Table 1). Smaller blue circles indicate 2009 - 2014 survey sites (coordinates in Longenecker *et al.* 2009, 2010, 2011, 2012, 2013a, 2014a). Adapted from chart Aus 523, published by the Australian Hydrographic Service. Depths are in meters.

from a single field trip to KWMA conducted one year after adoption of the plan. Pre-plan average lengths were estimated from baseline data obtained over a 6-year period prior to establishing the plan (*i.e.*, using a combined total 4,716 length estimated generated from 2009 to 2014).

Because the data sets for many species could not be transformed to meet parametric statistics' assumption of normality, we used the Mann-Whitney test (Minitab 17®) to test the null hypothesis that there is no difference in average fish length. We present results for any species meeting the five criteria for inclusion in the 2015 fishery survey (above) *and* for which we collected enough data to detect a change of less than 15% in average length (with a Type I error rate of 0.5 and a Type II error rate of 0.20) as determined by the sensitivity power analysis function of G*Power, version 3.1.9.2 (Faul *et al*. 2007).

If the relationship between length and weight was known, we converted length estimates to weight estimates, and present the change in average weight. If female size-at-maturity (♀L_{50}) was known, we estimated the percent of the population ≥ ♀L_{50}. If size-specific sex ratios were known, we estimated the percent of reproductive females in the population.

We constructed length-frequency histograms for each species for which at least 10 individuals were captured on video during 2015. To be included in the count of total number of individuals, a still image captured from video must have been of suitable quality for length estimation. If size-specific sex ratios were known, we showed the estimated number of reproductive females in each size class. The length information presented below is the distance between the front of the head and the end of the middle caudal ray.

RESULTS

Fishery Surveys

The average maximum depth of 2015 (post-plan) surveys was 27.8 m. A Mann-Whitney test indicates this is significantly shallower than the average maximum depth of all pre-plan dives (42.6 m).

In 2015, we captured 1,246 specimens on video suitable for length estimation. Sensitivity power analysis suggests data sets for 18 species are robust enough to detect a change of less than 15% in average length. The remainder of this report focuses solely on those 18 species.

We detected a significant difference in average pre- and post-plan length for 11 of 18 species (Figure 4). Nine species (50%) were significantly longer post-plan. Thus, 16 species (89%) of species are, statistically, the same size or larger one year after the KWMA reef-fish management plan was enacted.

Weighted-average percent length change was 11.2%, for the subset 8 species for which we have length-weight relationships, weighted-average percent weight change was 46.2%.

For the subset of eight species with published ♀L_{50} values, weighted-average length was 102% of female reproductive length, representing a post-plan increase of 14%. For the seven species with published size-specific sex ratios, the weighted average of the estimated percentage of reproductive females was 30% (a post-plan increase of 11%).

For 7 of the 8 species for which size-at-maturity is known, a free-swimming individual is more likely than not to be mature. The sole exception is *Cephalopholis cyanostigma* (*ikula sa*), for which the female size-at-maturity estimate is problematic (*i.e.*, may be overestimated). Thus, all individuals of the species presented in Table 3 may be more likely than not to be mature.

Detailed demographic information for each of 18 species is presented below. When at least 10 individuals were captured on video suitable for length estimates, we generated size-frequency histograms, with arrows indicating pre-plan average length.

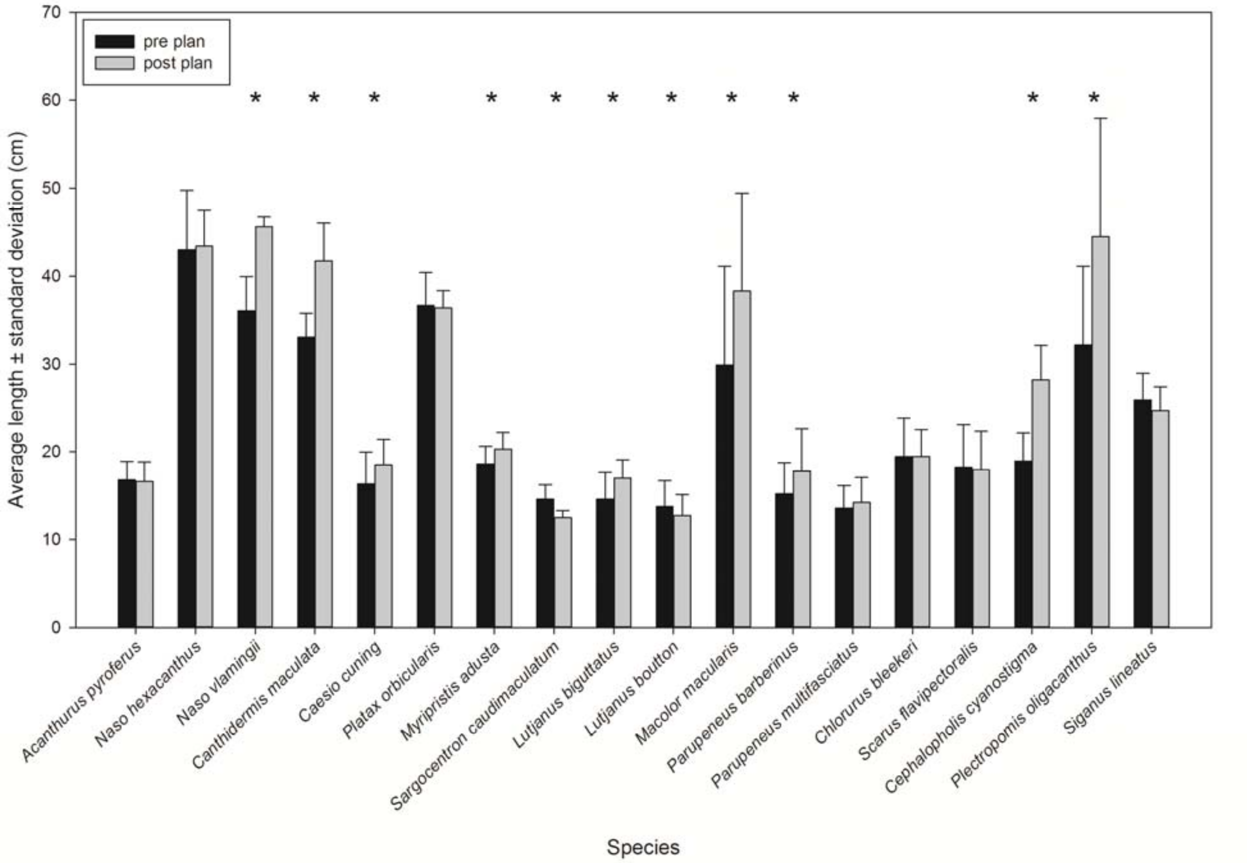


Figure 4. Average length of exploited reef fishes before and after adoption of the KWMA reef-fish management plan. Asterisks indicate a significant difference.

Table 2. Absolute and relative changes in length and weight of exploited reef fishes after adoption of the KWMA reef-fish management plan. Asterisks identify species for which a significant difference in length was detected. Superscripts in the weight change (g) column indicate the source of length-weight relationships.

Family	Species	Kala name(s)	Length change		Weight change	
			cm	%	g	%
Acanthuridae	*Acanthurus pyroferus*	not yet recorded	-0.2	-1.2	---	---
	Naso hexacanthus	*biaŋgawe suwi*	0.4	0.1	---	---
	*Naso vlamingii**	*biaŋgawe tumi*	9.5	26.4	---	---
Balistidae	*Canthidermis maculata**	*labaikã suwi*	8.7	26.2	---	---
Caesionidae	*Caesio cuning**	*luduŋ mai*	2.2	13.2	41.4[1]	36.4
Ephippidae	*Platax orbicularis*	not yet recorded	-0.3	-0.1	---	---
Holocentridae	*Myripristis adusta**	*imbilĩ tombo yeyẽ*	1.7	9.3	57.1[2]	32.3
	*Sargocentron caudimaculatum**	*imbilĩ yasai*	-2.1	-14.5	---	---
Lutjanidae	*Lutjanus biguttatus**	*itale*	2.4	16.6	21.5[3]	46.7
	*Lutjanus boutton**	*iyayaŋ*	-1.0	-7.3	---	---
	*Macolor macularis**	*labaikã tewe yayã*	8.4	28.1	---	---
Mullidae	*Parupeneus barberinus**	*iwaŋgale*	2.6	17.0	49.0[4]	64.9
	Parupeneus multifasciatus	*iwaŋgale bote*	0.6	4.6	7.2[5]	16.6
Scaridae	*Chlorurus bleekeri*	*iŋga bobo & iŋga talã*	<0.1	0.1	---	---
	Scarus flavipectoralis	*iŋga talaŋ & iŋga tali lau*	-0.3	-1.6	---	---
Serranidae	*Cephalopholis cyanostigma**	*ikula sa*	9.3	49.0	49.5[4]	43.8
	*Plectropomus oligacanthus**	*ikula su tatalõ*	12.3	38.2	1096.4[2]	198.6
Siganidae	*Siganus lineatus*	*yulawe*	-1.2	-4.6	-49.5[4]	-12.5

(1) Longenecker *et al*. 2014c, (2) Longenecker *et al*. 2013a, (3) Longenecker *et al*. 2013b, (4) Longenecker *et al*. 2011, (5) Longenecker & Langston 2008

Table 3. Percent of individuals larger than female size-at-maturity and estimated percent of adult females in eight exploited reef fishes at KWMA in 2015, plus the change from pre-plan estimates. Asterisks identify species for which a significant difference in length was detected. Superscripts in the % > ♀ L_{50} column indicate the source of reproductive information (listed under Table 2).

Family	Species	Kala name(s)	> ♀ L_{50}		Adult ♀	
			%	change	%	change
Caesionidae	*Caesio cuning**	*luduŋ mai*	120[1]	13	50	14
Holocentridae	*Myripristis adusta**	*imbilĩ tombo yeyẽ*	112[2]	6	45	-15
Lutjanidae	*Lutjanus biguttatus**	*itale*	100[3]	12	34	17
Mullidae	*Parupeneus barberinus**	*iwaŋgale*	150[4]	25	36	-9
	Parupeneus multifasciatus	*iwaŋgale bote*	93[5]	0	17	3
Serranidae	*Cephalopholis cyanostigma**	*ikula sa*	122[4]	39	25	-12
	*Plectropomus oligacanthus**	*ikula su tatalõ*	163[2]	44	---	---
Siganidae	*Siganus lineatus*	*yulawe*	104[4]	-4	40	8

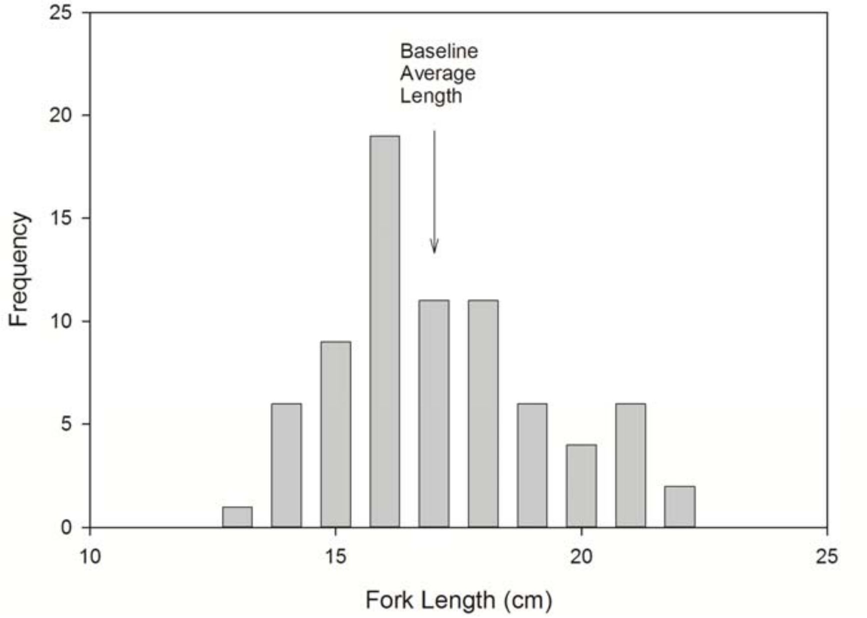
Species Accounts

Acanthuridae

***Acanthurus pyroferus* Kittlitz, 1834**; Kala name not yet recorded. Figure 5.

75 individuals were captured on video in 2015 (Figure 6), yielding a post-plan average fork length of 17 cm. This length was not significantly different from the pre-plan average length.

← Figure 5. *Acanthurus pyroferus*. Inter-laser distance 32 mm.

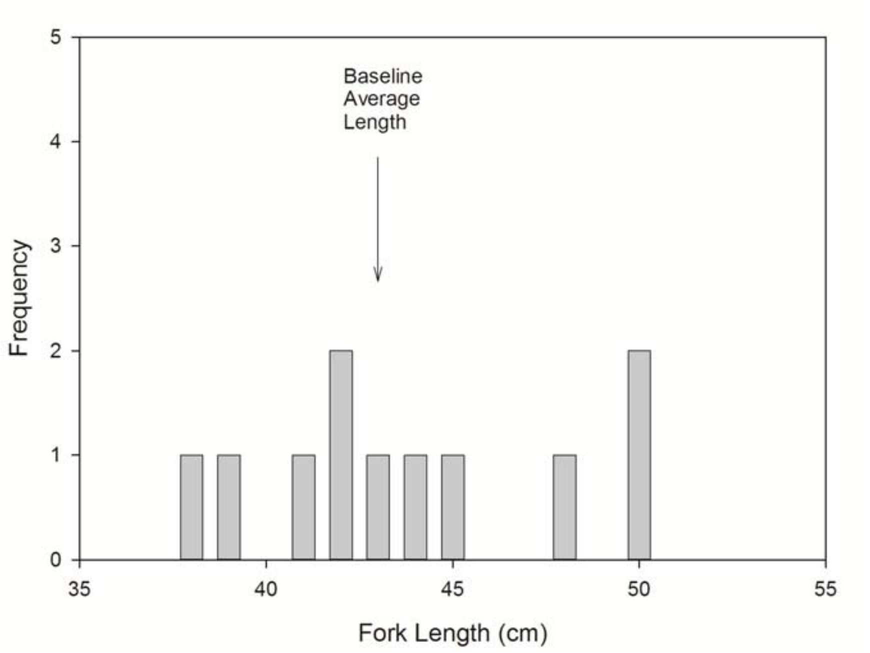


← Figure 6. Post-plan size structure of *Acanthurus pyroferus*.

Naso hexacanthus* (Bleeker, 1855)** or ***biaŋgawe suwi. Figure 7.

11 individuals were captured on video in 2015 (Figure 8), yielding a post-plan average "fork" length of 43 cm. This length was not significantly different from the pre-plan average length.

← Figure 7. *Biaŋgawe suwi* (*Naso hexacanthus*). Inter-laser distance 36 mm.



← **Figure 8. Post-plan size structure of *Naso hexacanthus*.**

Naso vlamingii* (Valenciennes, 1835)** or ***biaŋgawe tumi. Figure 9.

3 individuals were captured on video in 2015, yielding a post-plan average “fork” length of 46 cm. This length represents a statistically significant increase from the pre-plan average length of 36 cm.

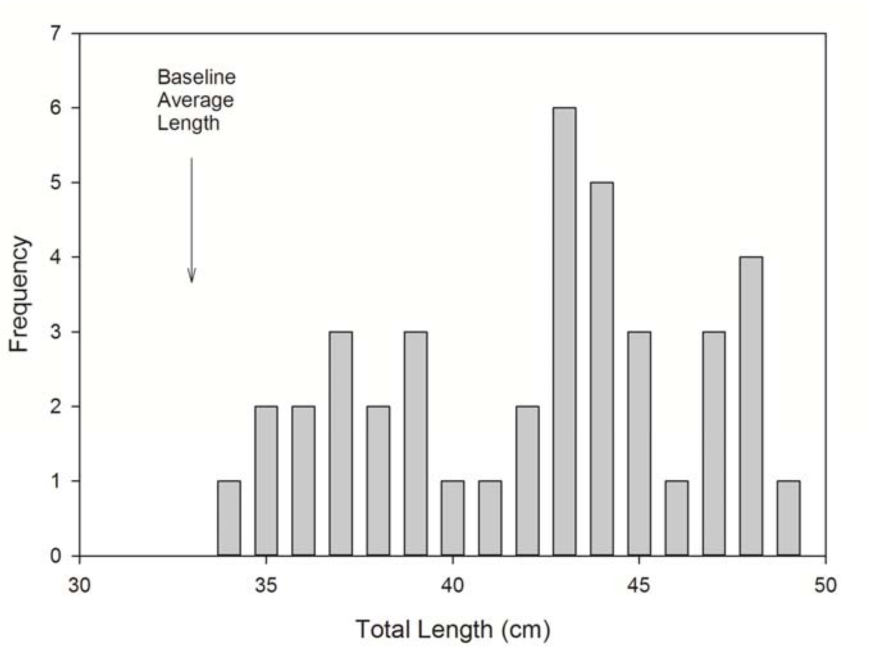
← **Figure 9. *Biaŋgawe tumi* (*Naso vlamingii*).**

Balistidae

Canthidermis maculata* (Bloch, 1786)** or ***labaikã suwi. Figure 10.

40 individuals were captured on video in 2015 (Figure 11), yielding a post-plan average fork length of 42 cm. This length represents a statistically significant increase from the pre-plan average length of 33 cm.

← **Figure 10. *Labaikã suwi* (*Canthidermis maculata*). Inter-laser distance 36 mm.**



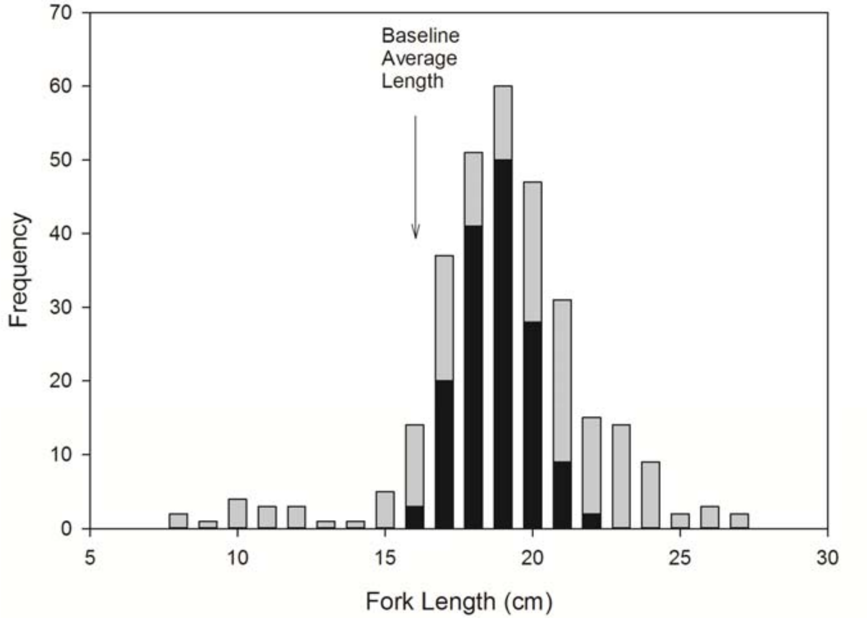
← **Figure 11. Post-plan size structure of *Canthidermis maculata*.**

Caesionidae

Caesio cuning* (Bloch, 1791)** or ***luduŋ mai. Figure 12.

Figure 12. *Luduŋ mai* (*Caesio cuning*). Inter-laser distance 31.5 mm.

305 individuals were captured on video in 2015 (Figure 13), yielding a post-plan average fork length of 18 cm. This length represents a statistically significant increase from the pre-plan average length of 16 cm. Average weight increased 41 g, representing a 36% increase from the pre-plan average weight. Average length increased to 120% of ♀L_{50} (15 cm) from the pre-plan value of 107%. We estimate that 50% of the post-plan population are mature females (versus 36% in the pre-plan population).



← Figure 13. Post-plan size structure of *Caesio cuning*. The dark portion of bars represent estimated number of mature females, light portion represents all other individuals.

Ephippidae

***Platax orbicularis* (Forsskål, 1775)**; Kala name not yet recorded. Figure 14.

6 individuals were captured on video in 2015, yielding a post-plan average fork length of 36 cm. This length was not significantly different from the pre-plan average length.

← Figure 14. *Platax orbicularis*. Inter-laser distance 32 mm.

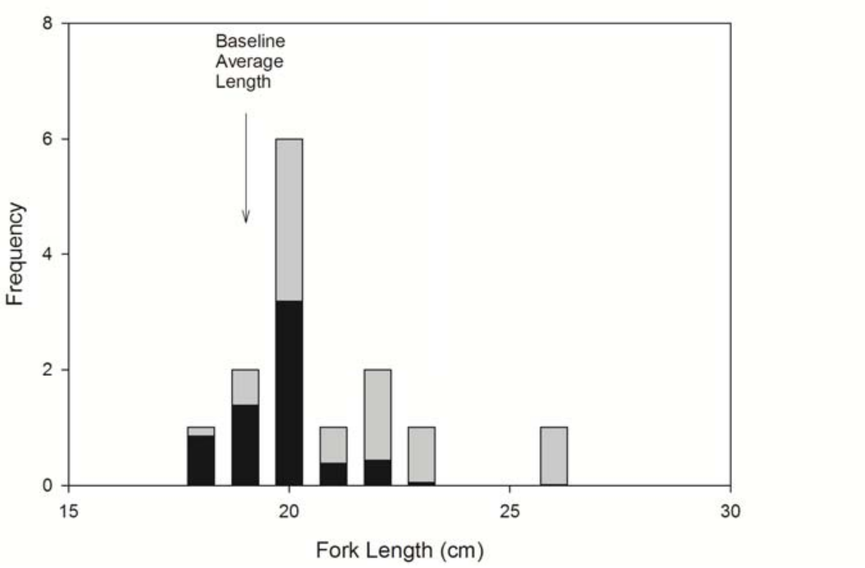
Holocentridae

Myripristis adusta* Bleeker, 1853** or ***imbilĩ tombo yeyẽ. Figure 15.

Figure 15. *Imbilĩ tombo yeyẽ* (*Myripristis adusta*).

14 individuals were captured on video in 2015 (Figure 16), yielding a post-plan average fork length of 20 cm. This length represents a significantly significant increase from the pre-plan average length of 19 cm. Average weight increased 57 g, representing a 32% increase from the pre-plan average weight. Average length increased to 118% of ♀L_{50} (17 cm) from the pre-plan value of 112%. We estimate that 45% of the post-plan population are mature females (versus 60% in the pre-plan population). The

counterintuitive decrease in the percentage of mature females, despite an increase in reproductively sized individuals is caused by the phenomenon of females becoming increasingly rare in larger size classes (Longenecker *et al*. 2013a).



← Figure 16. Post-plan size structure of *Myripristis adusta*. The dark portion of bars represent estimated number of mature females, light portion represents all other individuals.

Sargocentron caudimaculatum* (Rüppell, 1838)** or ***imbilĩ yasai. Figure 17.

5 individuals were captured on video in 2015, yielding a post-plan average fork length of 12 cm. This length was not significantly different from pre-plan average length.

← Figure 17. *Imbilĩ yasai* (*Sargocentron caudimaculatum*). Inter-laser distance 31 mm.

Lutjanidae

Lutjanus biguttatus* (Valenciennes, 1830)** or ***itale. Figure 18.

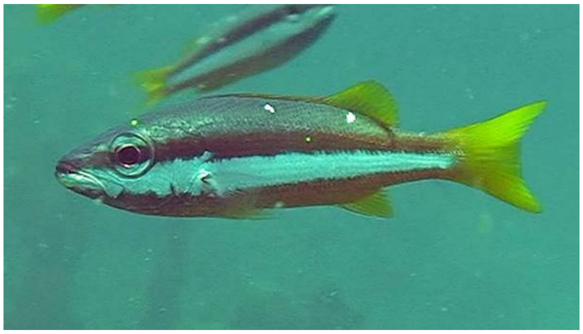
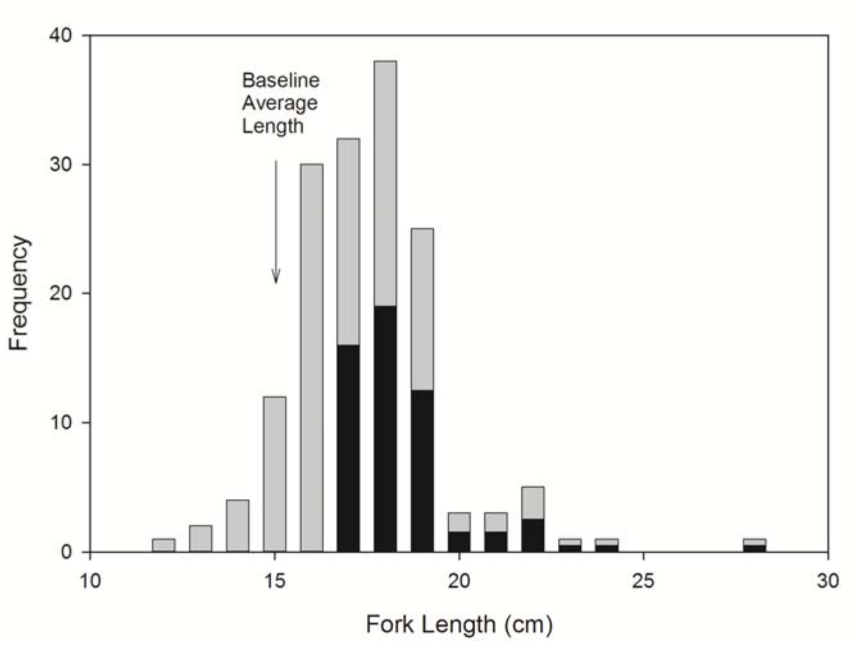


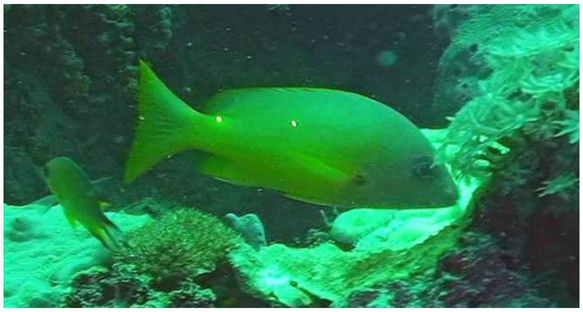
Figure 18. *Itale* (*Lutjanus biguttatus*). Inter-laser distance 39 mm.

158 individuals were captured on video in 2015 (Figure 19), yielding a post-plan average fork length of 17 cm. This length represents a significant increase from the pre-plan average length of 15 cm. Average weight increased 22 g, representing a 47% increase from the pre-plan average. Average length increased to 100% of ♀L_{50} (17 cm) from the pre-plan values of 88%. We estimate that 34% of the post-plan population are mature females (versus 17% in the pre-plan population).



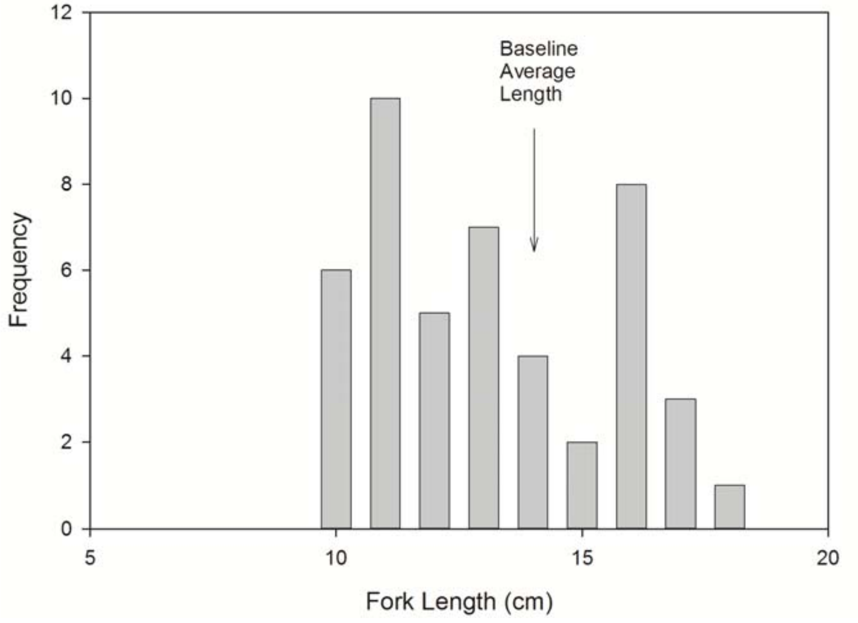
← Figure 19. Post-plan size structure of *Lutjanus biguttatus*. The dark portion of bars represent estimated number of mature females, light portion represents all other individuals.

Lutjanus boutton* (Lacepède, 1802)** or ***iyayaŋ. Figure 20.



46 individuals were captured on video in 2015 (Figure 21), yielding a post-plan average fork length of 13 cm. This length represents a significant decrease from the pre-plan average length of 14 cm.

← Figure 20. *Iyayaŋ* (*Lutjanus boutton*). Inter-laser distance 39 mm.

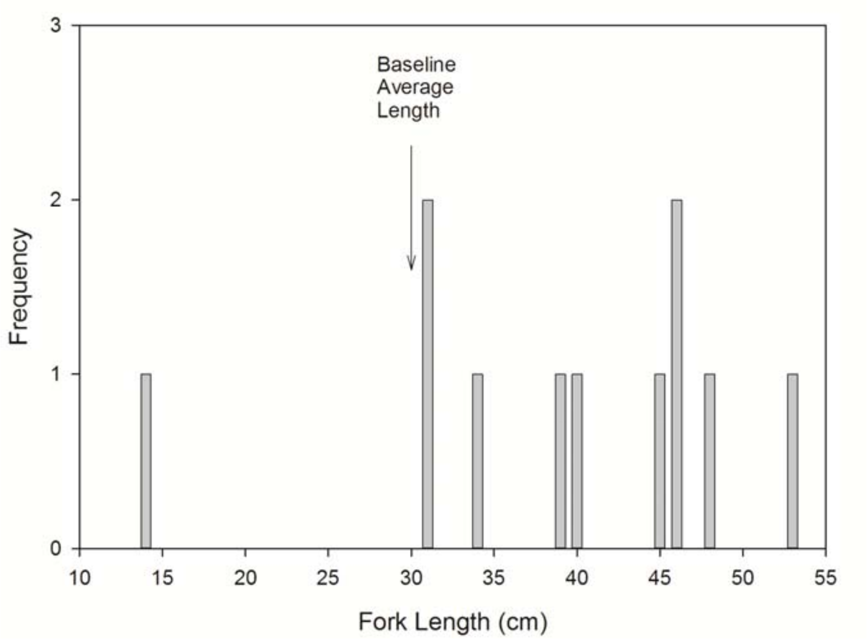


← Figure 21. Post-plan size structure of *Lutjanus boutton*.

Macolor macularis **Fowler, 1931** or ***labaikã tewe yayã***. Figure 22.

11 individuals were captured on video in 2015 (Figure 23), yielding a post-plan average fork length of 38 cm. This length represents a significant increase from the pre-plan average length of 30 cm.

← Figure 22. *Labaikã tewe yayã* (*Macolor macularis*).



← Figure 23. Post-plan size structure of *Macolor macularis*.

Mullidae

Parupeneus barberinus **(Lacepède, 1801)** or ***iwaŋgale***. Figure 24.

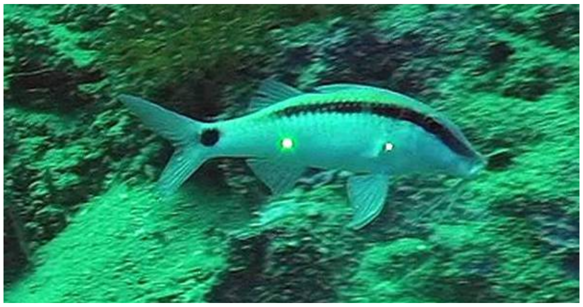
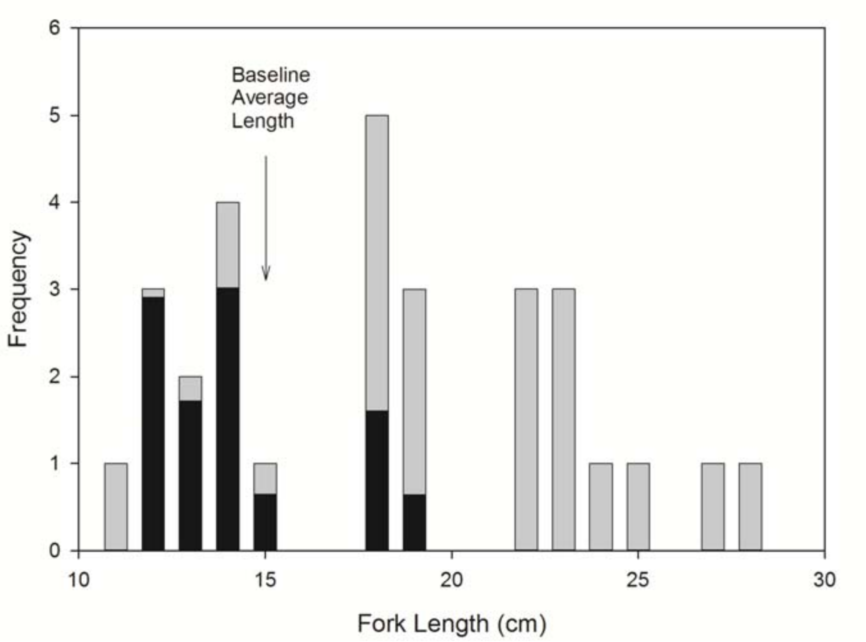


Figure 24. *Iwaŋgale* (*Parupeneus barberinus*). Inter-laser distance 39 mm.

29 individuals were captured on video in 2015 (Figure 25), yielding a post-plan average fork length of 18 cm. This length represents a significant increase from the pre-plan average length of 15 cm. Average weight increased 49 g, representing a 65% increase from the pre-plan average weight. Average length increased to 150% of ♀L_m (12 cm) from the pre-plan value of 125%. We estimate that 36% of the post-plan population are mature females (versus 45% in the pre-plan population. The counterintuitive decrease in the percentage of mature females, despite an

increase in reproductively sized individuals is caused by the phenomenon of females becoming increasingly rare in larger size classes (Longenecker *et al.* 2011).

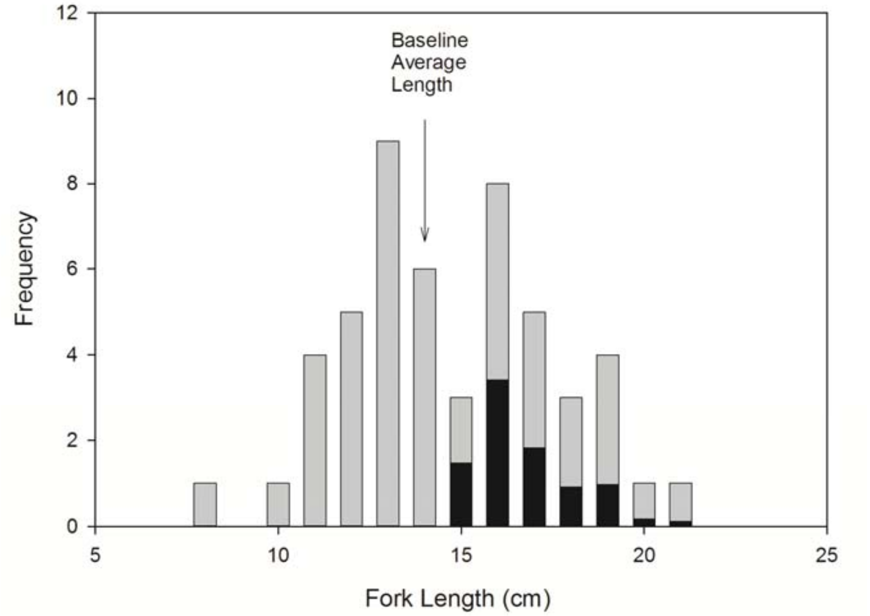


← Figure 25. Post-plan size structure of *Parupeneus barberinus*. The dark portion of bars represent estimated number of mature females, light portion represents all other individuals.

Parupeneus multifasciatus* (Quoy & Gaimard, 1825)** or ***iwaŋgale bote. Figure 26.

Figure 26. *Iwaŋgale bote* (*Parupeneus multifasciatus*).

51 individuals were captured on video in 2015 (Figure 27), yielding a post-plan average fork length of 14 cm. This length was not significantly different from the pre-plan average length. Average weight increased 7 g, representing a 17% increase from the pre-plan average weight. Average length is 93% of ♀L_{50} (15 cm), and unchanged from the pre-plan value. We estimate that 17% of the post-plan population are mature females (versus 14% in the pre-plan population).



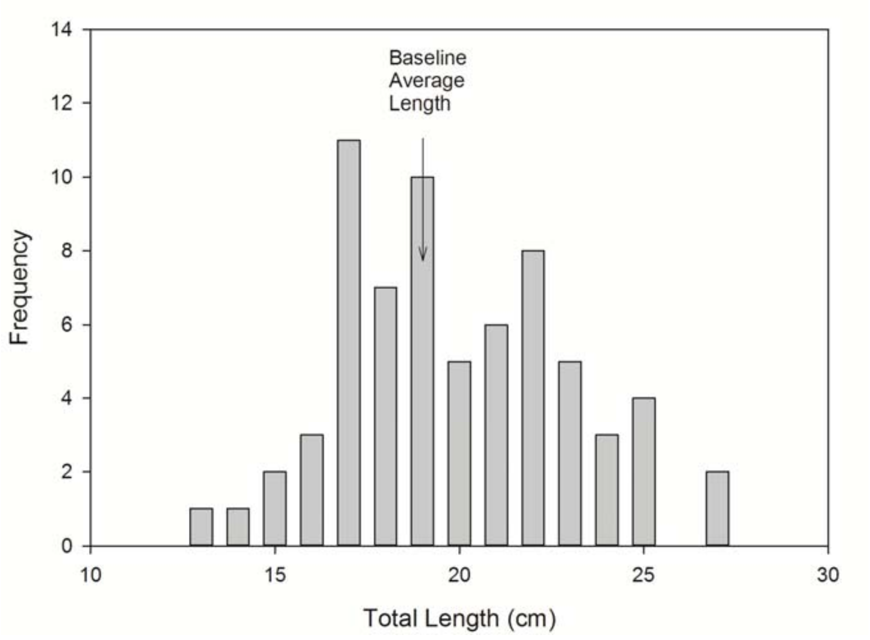
← **Figure 27. Post-plan size structure of *Parupeneus multifasciatus*. The dark portion of bars represent estimated number of mature females, light portion represents all other individuals.**

Scaridae

Chlorurus bleekeri* (de Beaufort, 1940)** or ***iŋga bobo (initial phase) and ***iŋga talã*** (terminal male). Figure 28.

Figure 28. *Iŋga bobo* (left) and *iŋga talã* (right) or *Chlorurus bleekeri* initial phase (left) and terminal male (right). Inter-laser distance 31.5 mm.

68 individuals were captured on video in 2015 (Figure 29), yielding a post-plan average total length of 19 cm. This length was not significantly different from the pre-plan average length.

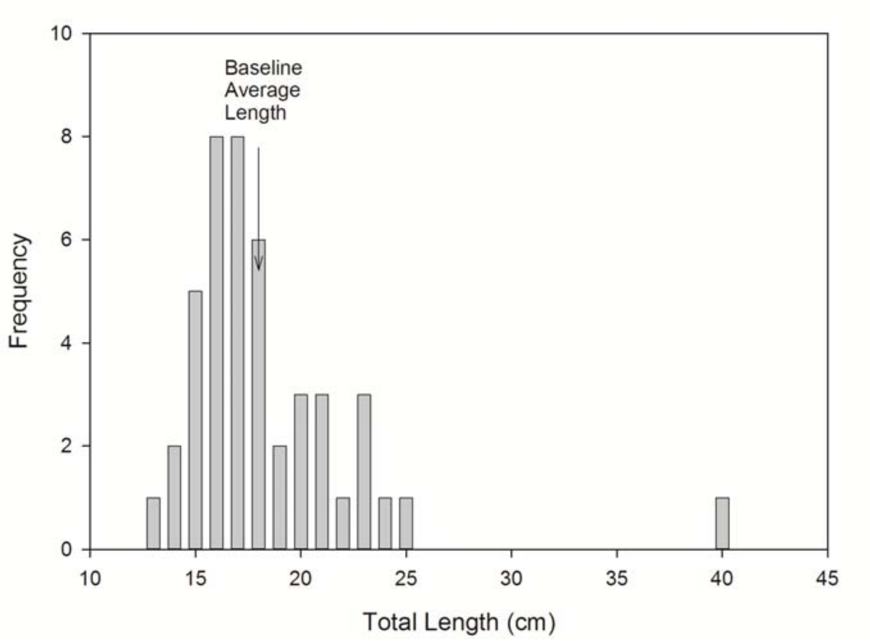


← **Figure 29. Post-plan size structure of *Chlorurus bleekeri*.**

Scarus flavipectoralis* Schultz, 1958** or ***iŋga talaŋ (initial phase) and ***iŋga tali lau*** (terminal male). Figure 30.

Figure 30. *Iŋga talaŋ* (left) and *iŋga tali lau* (right) or *Scarus flavipectoralis* initial phase (left) and terminal male (right). Inter-laser distance 36 and 39 mm, respectively.

45 individuals were captured on video in 2015 (Figure 31), yielding a post-plan average total length of 18 cm. This length was not significantly different from the pre-plan average length.



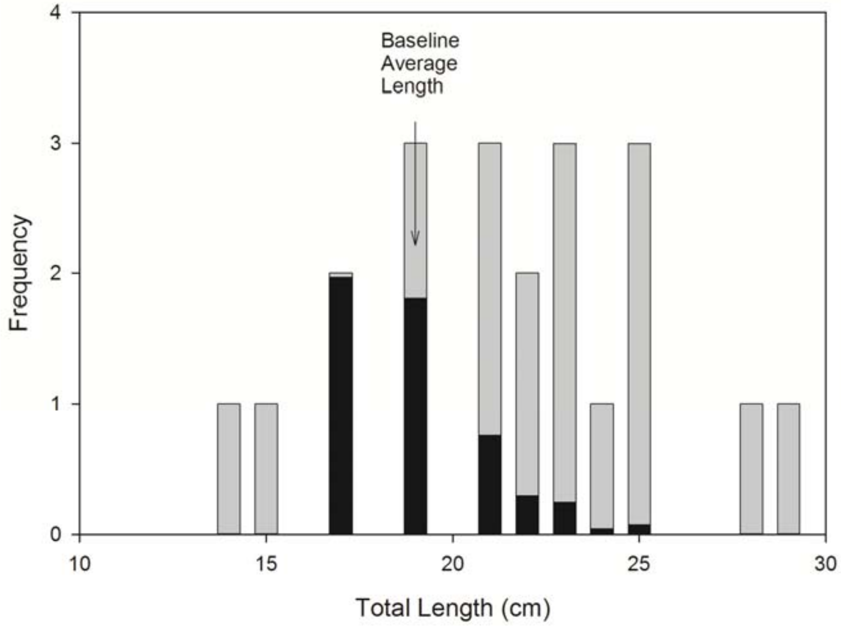
← Figure 31. Post-plan size structure of *Scarus flavipectoralis*.

Serranidae

Cephalopholis cyanostigma* (Valenciennes, 1828)** or ***ikula sa. Figure 32.

Figure 32. *Ikula sa* (*Cephalopholis cyanostigma*). Inter-laser distance 39 mm.

21 individuals were captured on video in 2015 (Figure 33), yielding a post-plan average total length of 28 cm. This length represents a significant increase from the pre-plan average length of 19 cm. Average weight increased 50 g, representing a 44% increase from the pre-plan average weight. Average length increased to 122% of ♀L_{50}, (23 cm), from the pre-plan value of 83%. We estimate that 25% of the post-plan population are mature females (versus 37% in the pre-plan population). The counterintuitive decrease in the percentage of mature females, despite an increase in reproductively sized individuals is caused by the phenomenon of females becoming increasingly rare in larger size classes (Longenecker *et al.* 2011). Further, our estimate of the percentage of mature females is based on minimum size-at-maturity (L_m). If a problematic estimate of ♀L_{50} (Longenecker *et al.* 2011) is used, as few as 0.8 % or 1.7% may be mature females (pre- and post-plan, respectively).



← Figure 33. Size structure of *Cephalopholis cyanostigma*. The dark portion of bars represent estimated number of mature females, light portion represents all other individuals.

Plectropomus oligacanthus* (Bleeker, 1855)** or ***ikula su tatalõ. Figure 34.

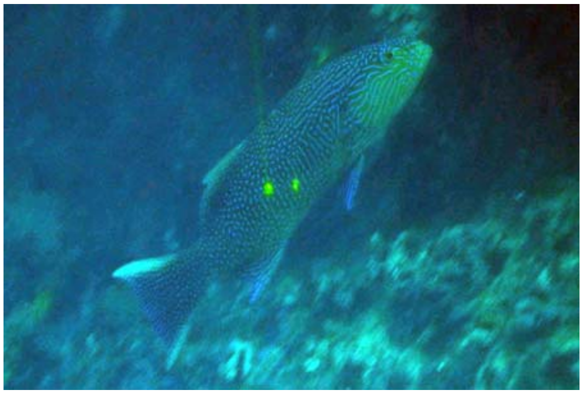
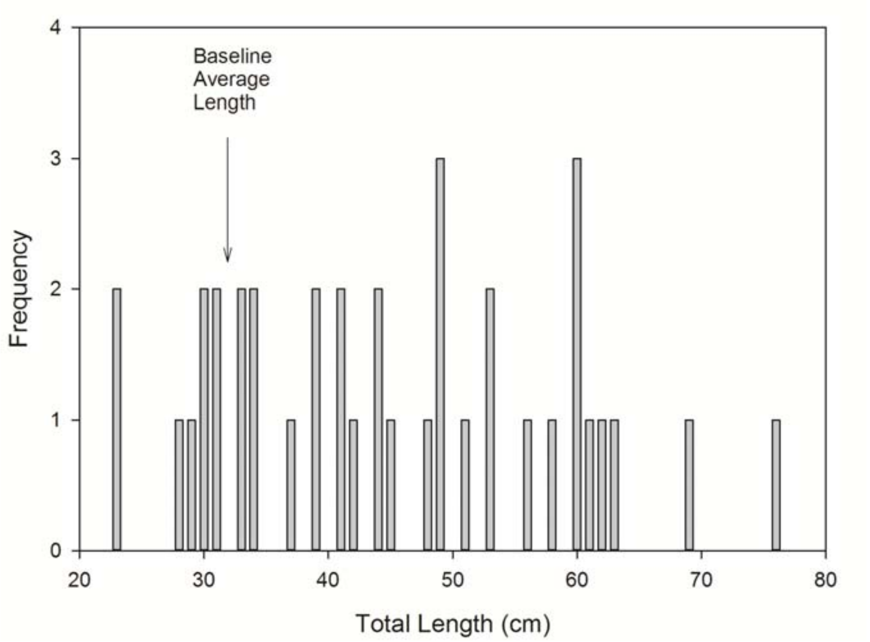


Figure 34. *Ikula su tatalõ* (*Plectropomus oligacanthus*). Inter-laser distance 31.5 mm.

38 individuals were captured on video in 2015 (Figure 35), yielding a post-plan average total length of 44 cm. This length represents a significant increase from the pre-plan average length of 32 cm. Average weight increased 1096 g, representing a 199% increase from the pre-plan average weight. Average length increased to 163% of ♀L_m (27 cm) from the pre-plan value of 119%



← **Figure 35. Size structure of *Plectropomus oligacanthus*.**

Siganidae

Siganus lineatus* (Valenciennes, 1835)** or ***yulawe. Figure 36.

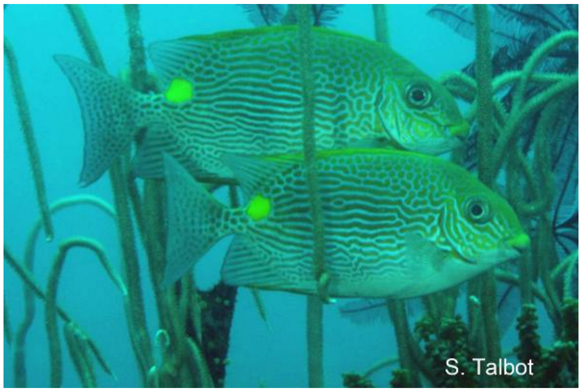
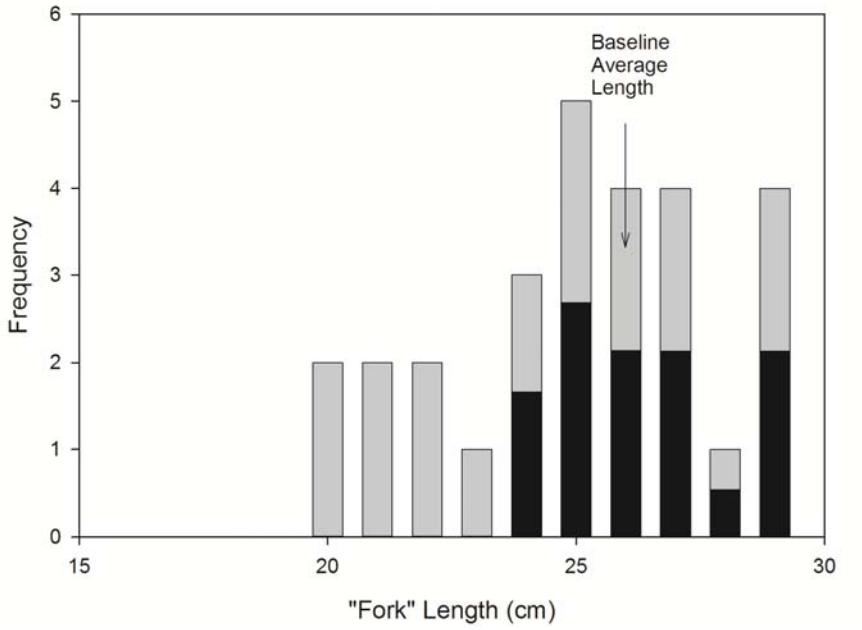


Figure 36. *Yulawe* (*Siganus lineatus*).

28 individuals were captured on video in 2015 (Figure 37), yielding a post-plan average "fork" length of 25 cm. This length was not significantly different from the pre-plan average length. Average weight decreased 50 g, representing a 13% decrease from the pre-plan average weight. Average length decreased to 104% of ♀L_{50} (24 cm) from the pre-plan value of 108%. We estimate that 40% of the post-plan population are mature females (versus 32%) in the pre-plan population).



← Figure 37. Post-plan size structure of *Siganus lineatus*. The dark portion of bars represent estimated number of mature females, light portion represents all other individuals.

DISCUSSION

Plan Evaluation

One year after the enactment of a reef-fish management plan at KWMA, average fish length increased by 11.2%, average weight increased 46.2%, the percentage of reproductively sized individuals increased 14%, and the percentage of mature females increased 11%. These results suggest that the management plan had a positive effect on coral-reef fish populations at KWMA such that residents' current dietary needs and economic desires of can be more easily met while helping to insure viable fish populations for future generations.

However, the changes we describe were so fast and so profound that they challenge the credibility of our results. There are at least three alternative, non-exclusive, scenarios that could cause the changes we describe (and thus make questionable the impact of the management plan). We list the possibilities here, and discuss each one individually, below:

1. Because of an equipment failure, post-plan surveys were conducted in significantly shallower water than pre-plan surveys. We may have compared fish populations in fundamentally different habitats.
2. We may have introduced a systematic measurement error. For instance, if our lasers were not properly calibrated, actual inter-laser distance could have been less than the nominal distance. This would cause an overestimation of fish length.
3. A recent recruitment failure could result in increased average length while the number of fish in a population is actually decreasing. Fewer young (*i.e.*, small) fish would raise the population-level average length some time before a population decline could be detected by our methods.

Depth

Average lengths were generally larger post-plan, when we worked in significantly shallower water. The change in average length may have been caused by an unintentional change in depth. It is commonly hypothesized that deeper water provides a refuge from fishing, similar to a marine protected area (Tyler *et al*. 2009, Kahng *et al*. 2010, Goetze *et al*. 2011, Lindfield *et al*. 2014), where the size of fish can increase relative to shallower, fished areas (*i.e.*, the general expectation would be counter to our results). However, evaluation depth-related changes in fish length is limited and the results are equivocal (Lindfield *et al*. 2014, Pyle *et al*. submitted); there is no strong evidence that a change in depth should cause a corresponding change in average length.

Further, our casual observations while working in deeper water during pre-plan surveys indicate that fish are much less common in deeper water (> 46 m) at KWMA than on shallower coral reefs. It is unlikely that the relatively few deeper water fish we captured on video during pre-plan surveys would significantly influence average length calculations for the species examined in this report.

Systematic measurement error

A systematic measurement error could overestimate fish lengths, for instance if the actual inter-laser distance was less than the nominal distance used to solve for equivalent ratios when estimating fish lengths from video surveys. This type of error would have a predictable effect such that the difference between estimated and actual length would be progressively larger with increasing fish size (Figure 38). Assuming no real difference in average length between pre- and post-plan surveys, we would see a similar pattern in the change in absolute length from pre-plan average lengths. However, linear regression analysis of the change in average length as a function of pre-plan average length (Figure 39) was not significant, suggesting that our observation of a general post-plan increase in average length was not a result of systematic measurement error.

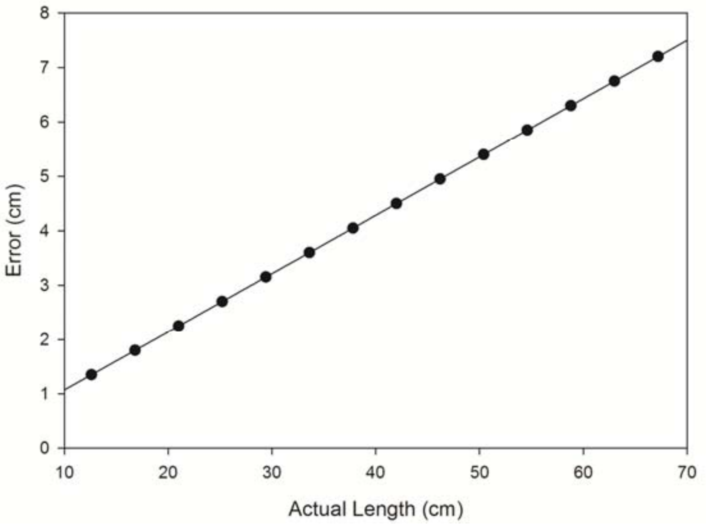


Figure 38. A simulation of systematic measurement error, assuming that actual inter-laser distance was 28 mm when nominal interlaser distance was 31 mm. Absolute error increases predictably with fish length.

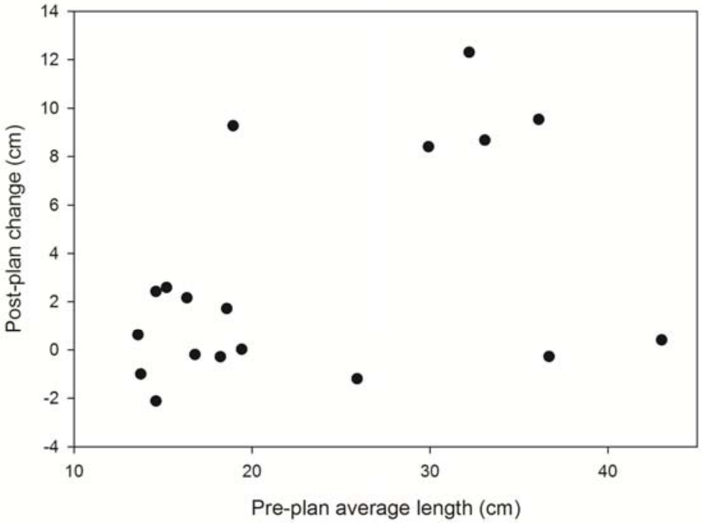


Figure 39. Test for systematic measurement error. The relationship between average pre-plan fish length and the difference from post-plan length was not significant.

<u>Recruitment failure</u> – Larger average size can be seen if fish populations fail to produce young fish (*i.e.*, if there are fewer small fish in the population). In this case, a size-frequency histogram would have fewer small fish than had been recorded in earlier years ***and*** would have approximately the same number and sizes of larger fish seen in previous years. Figure 40 shows an example of recruitment failure. In a typical population (left), average length is 14.8 cm. If the five smallest size classes (representing 17% if individuals) are missing, yet the remainder of the population is unchanged (right), average length increases 1 cm (7%). Figure 41 shows the pre- and post-plan size structure of the 14 species for which we plotted size structure. Of these, only two species (*M. adusta* and *L. biguttatus*) appear to be candidates for recruitment failure; the smallest size classes, representing at least 15% of the population were missing in 2015. These species warrant further monitoring.

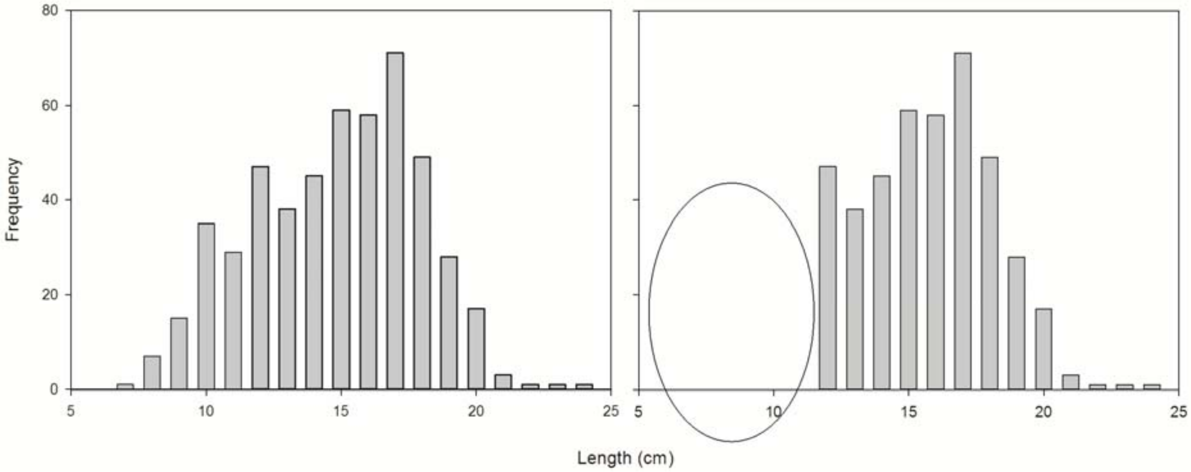


Figure 40. A graphical representation of recruitment failure. The left plot shows the typical size structure of a population at KWMA based on laser-videogrammetry surveys. The right plot shows the size structure of the same population if the five smallest size classes are absent (indicated by the oval).

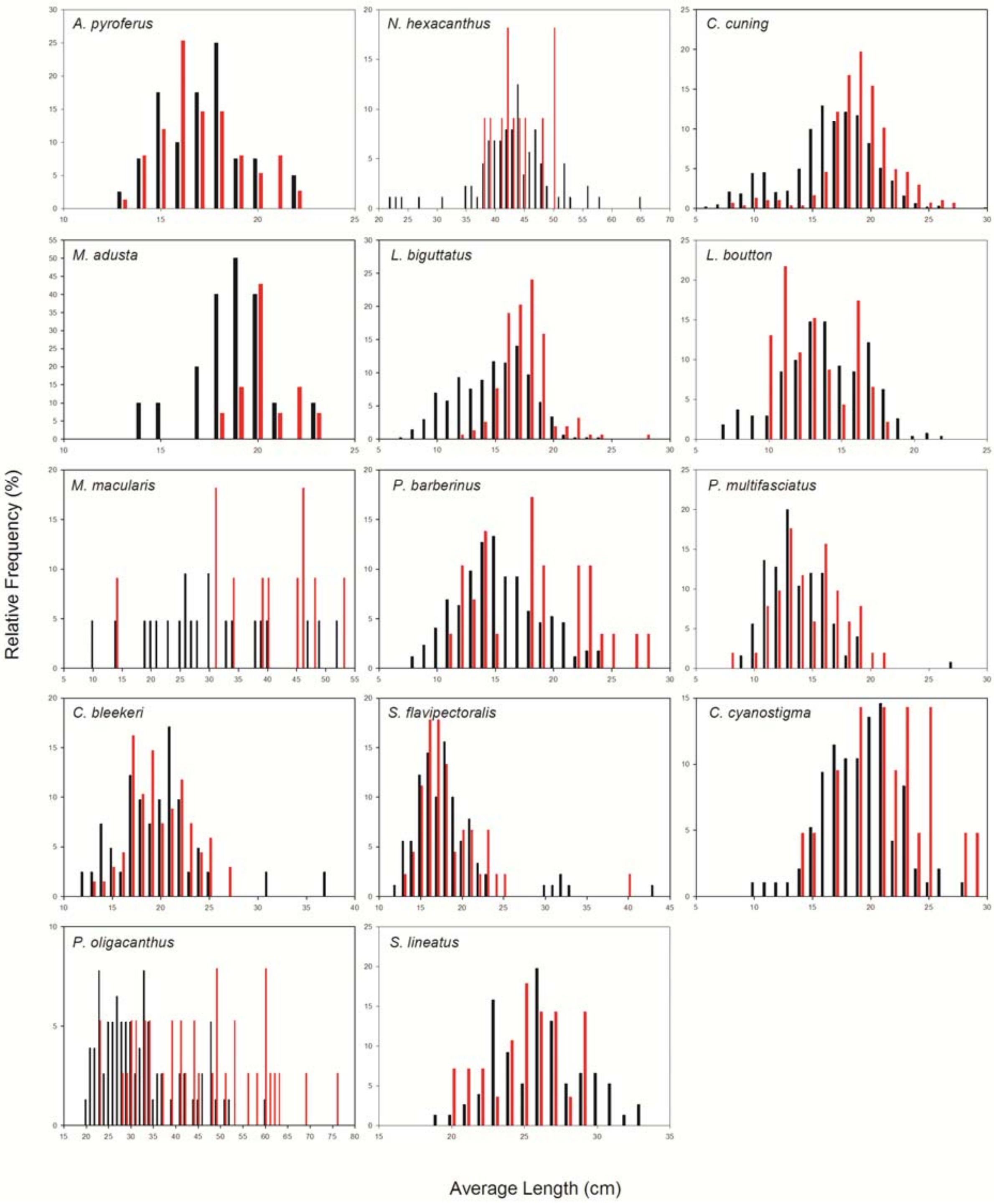


Figure 41. Graphical analysis of potential recruitment failure. Pre-plan size structure is plotted in black, post-plan in red.

Recommendations

We do not think that the desirable results we describe in this report resulted from an unintentional change in working depth, systematic measurement error, or a recruitment failure. However, our post-plan data set is small. During pre-plan work, we found that it took 3 to 6 years of surveys before average length calculations stabilized (*i.e.*, to generate robust data sets). We strongly suggest that additional monitoring be performed before KWMA's reef-fish management plan is promoted elsewhere.

In the meantime, our results suggest that the plan has had a positive effect on KWMA's fish populations. For the species we studied, average length increased 11.2% and average weight increased 46.2%, thus KWMA residents should be able to more-easily meet their nutritional needs. At the same time, the percentage of reproductively sized individuals increased 14% and the percentage of mature females increased 11%. These changes should help insure that fish populations will be replenished and that future generations of KWMA residents will be able to meet their dietary needs. Given the current lack of evidence that KWMA's reef-fish management plan is detrimental to the village's fish populations, we suggest that residents continue adhering to the plan.

ACKNOWLEDGMENTS

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