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Fisheries Resources of Pitcairn Island: Assessment and Management Challenges

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Declaration of Own Work

I declare that this thesis, "Fisheries Resources of Pitcairn Island: Assessment and Management Challenges", is entirely my own work, and that where material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given.

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Table of Contents

List of Acronyms

BRUV: Baited Remote Underwater Videography

DOV: Diver Operated Video

EEZ: Exclusive Economic Zone

GPS: Global Positioning System

IRD: L'Institut de recherche pour le développement

HMAV: His Majesty's Armed Vessel

MV: Marine Vessel

NTA: No Take Area

SCUBA: Semi Closed Underwater Breathing Apparatus

SPC: Secretariat of the Pacific Community

UKOT: United Kingdom Overseas Territory

UVC: Underwater Visual Census

UVS: Underwater Visual Survey

UWA: University of Western Australia

ZSL: Zoological Society of London

Word Count: 14,992

Abstract

The marine environment of the Pitcairn Islands is known to contain near ‘pristine’ ecosystems which support unique fish assemblages in addition to endemic and threatened species. Pitcairn itself is the only inhabited island in the group, and the environmental impact of the local fishery is unclear, with insufficient evidence to inform conservation and fisheries management decisions.

In response to these issues, Pitcairn’s coastal fish assemblage was sampled using Baited Remote Underwater Videography (BRUV) a non-extractive technique recognised as a powerful tool for quantitatively assessing scientifically valuable habitats with minimal impact. Species richness, relative abundance and size data were obtained, allowing fish assemblage structure to be evaluated and compared with other sites.

BRUV recorded 88 species, including five new records for Pitcairn Island. Small-bodied herbivores and mesopredators were dominant, creating a ‘bottom heavy’ assemblage with trophic level 3.9 and below accounting for 73% of biomass. Several large pelagic carnivores were recorded but reef-associated top predators were rare. Comparative analysis indicated low species richness compared to eastern French Polynesia, reflecting acknowledged biogeographical patterns, and Pitcairn’s top predator assemblage was demonstrably impoverished compared to regional and global ‘pristine’ sites. The scarcity of top predators may be explained by the island’s artisanal fishery, which has historically targeted sharks and other large carnivores, while recent declines in fishing pressure are likely to have caused the observed proliferation of small-bodied species. This study indicates that a proposed commercial fishery on the island could lead to over-exploitation of some target species, and recommends the application of BRUV data to quotas for any future fishery.

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I sincerely hope this thesis will support the future sustainability and conservation of marine resources on Pitcairn Island, and I hope to continue my involvement in studying the unique biodiversity of these islands in the future.

Chapter 1: Introduction

1.1 Geography

The Pitcairn Islands group is located in the South Pacific, 500km east of the easternmost inhabited island in French Polynesia and over 2,000km west of Easter Island which is the only human habitation between the Pitcairns and South America (Irving & Dawson, 2012) (Figure 1.1).

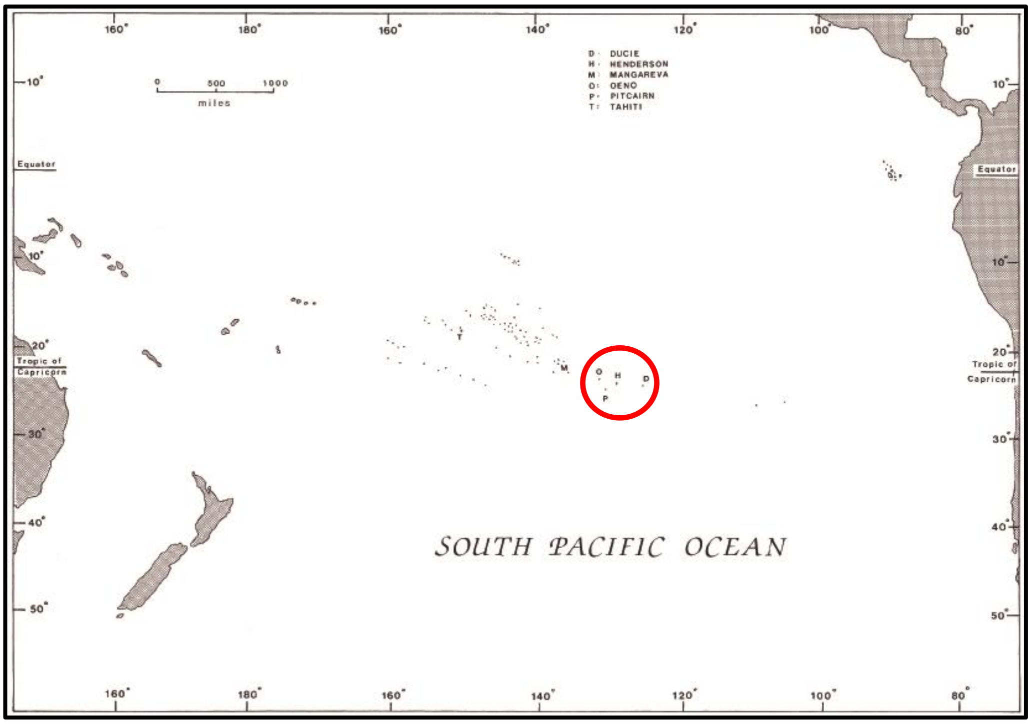

Figure 1.1 The location of the Pitcairn Islands (circled in red) with South America to the east and Australia to the west (reproduced with permission from Irving & Dawson, 2012).

Pitcairn itself is estimated to be less than 1 million years old, one of numerous seamounts formed by a volcanic 'hotspot' area in the south Pacific, whilst Henderson, Ducie and Oeno are coral atolls (Figure 1.2) (Ake-Gotesson, 2012). Henderson is the largest of the four, with a land area of 4,310 hectares, and Oeno is the smallest at 65 hectares (Irving & Dawson, 2012).

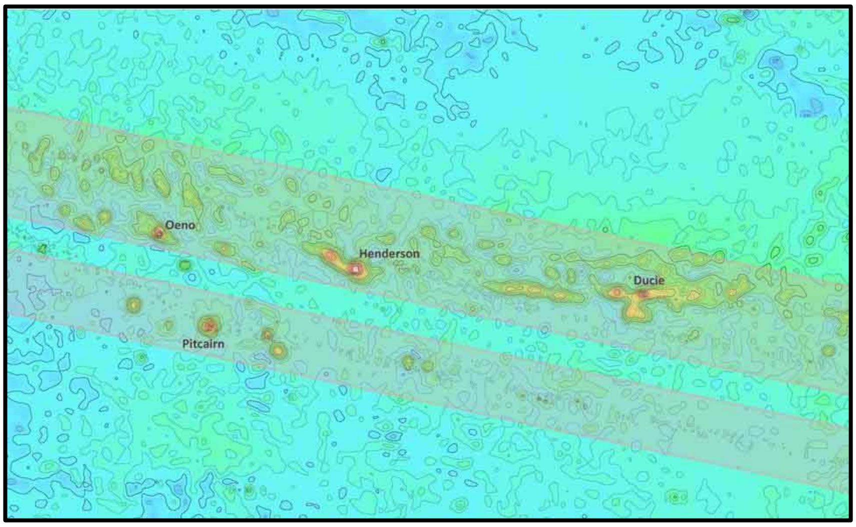

Figure 1.2 Seafloor bathymetry of the Pitcairn Islands, showing 'hotspot' zones of volcanic activity (shaded areas). Adapted from satellite altimetry data (Smith & Sandwell, 1997).

1.2 History

Of the four islands in the group, it is believed that only Pitcairn and Henderson have ever been inhabited. Evidence suggests that Polynesian settlers lived on both islands between roughly 900AD and 1450AD, with Henderson uninhabited since that time (Irving & Dawson, 2012). Pitcairn also remained uninhabited until 1790 when nine of the mutineers from HMAV Bounty landed on the island in search of refuge, accompanied by 14 Polynesians (Alexander, 2004). The arrival of the mutineers represents the foundation of modern Pitcairn, and many of the island's current population are directly descended from the Bounty's men and their Tahitian wives. The population of the island peaked in the mid-1900s at around 230 individuals, though has since declined to around 50 in 2014. In political terms, Pitcairn became a British dependency in 1838, followed by the other three islands in 1938. Today, the Pitcairn Islands are designated as a United Kingdom Overseas Territory (UKOT) and are the only remaining British territory in the Pacific (Irving & Dawson, 2012).

1.3 Marine Environment

Despite the small combined land area of the four islands, their Exclusive Economic Zone (EEZ) covers around 836,000km^2 of ocean. The remoteness of the island group has helped to ensure that their marine ecosystems have remained largely 'pristine' and unaffected by human activities, (Sala *et al.,* 2012, Friedlander *et al.,* in prep.). Marine species diversity in the Pitcairn Islands is 'impoverished' compared to French Polynesia and the Indo-Pacific Coral Triangle (due largely to the greater area of coral reefs in these regions), however the presence of developed corals at all four islands is itself remarkable as the group is located at the extreme limit of known tropical coral distribution (Irving & Dawson, 2012; Carpenter, 1998). Developed corals have been found at unprecedented depths, a phenomenon attributed to the 'extreme water clarity' around the islands, and the earth's deepest known coral reef was recently discovered at 75m near Pitcairn (Sala *et al.,* 2012). Moreover surveys by National Geographic in 2012 found that regional endemics comprised 45% of fish assemblages, creating unique species communities found nowhere else in the Pacific (Sala *et al.,* 2012). Species in the Pitcairns have primarily originated from the west, despite easterly prevailing winds and currents (Irving & Dawson, 2012), thus indicating that the island group is a 'stepping stone' between the Indo-Pacific and East Pacific biogeographic regions, acting as a physical 'conduit' for species movement (Irving *et al.*, 2012; Carpenter, 1998).

Furthermore the islands support 38 globally threatened species including green turtles (*Eretmochelys imbricate*), humpback whales (*Megaptera novaeangliae*), napoleon wrasse (*Cheilinus undulatus*) and hammerhead sharks (*Sphyraena* spp.) (Friedlander *et al.*, in prep.). Surveys of Ducie and Henderson atolls found that top predators accounted for more than half of fish biomass, demonstrating the health of the reefs and implying low fishing pressure (Friedlander *et al.*, in prep.). In summary, the marine ecosystems of the Pitcairn Islands are of 'outstanding' scientific value owing to their excellent condition and biological uniqueness (Sala *et al.,* 2012).

1.4 Darwin Project

Despite this recognition of the value of the marine environment of the Pitcairn Islands, these ecosystems are poorly studied and there is a lack of evidence to inform conservation and management (Dawson *et al.*, 2013). This issue is particularly urgent on Pitcairn itself where fishing has been an important socio-economic community activity over the last two centuries, with methods including line fishing from rocks or small boats, longlining in deep water and spear fishing (Irving & Dawson, 2012, Ake-Gotesson, 2012). The impact of this long term artisanal fishery is not sufficiently assessed, and the environmental and economic implications of the fishing pressure are unclear. National Geographic recorded substantially lower large carnivore biomass on Pitcairn compared to other islands in the group, suggesting that the fish assemblage has been negatively impacted (Sala *et al.*, 2012). Furthermore the Secretariat of the Pacific Community (SPC) recently published a feasibility study for the creation of a small commercial fishery on Pitcairn for export to Mangareva, the nearest island in French Polynesia which suffers from ciguatoxicity (Blanc, 2011; Sharp, 2011). The fishery would focus on three coastal species which are also popular for subsistence on Pitcairn; gray drummer (*Kyphosus pacificus*), blacktip grouper (*Epinephelus fasciatus*) and yellow-edged lyretail (*Variola louti*) (Sharp, 2011). An economically viable commercial fishery would require a substantial catch increase, as currently Pitcairners fish mainly for subsistence with rare opportunities to sell catch (Schuttenberg & Dawson, 2012; Ake-Gotesson, 2012). However, the information necessary to ensure the viability and sustainability of a commercial fishery is lacking Dawson *et al.*, 2013), and the SPC's report highlighted the need for quantitative evidence, particularly size data for blacktip grouper and yellow-edged lyretail (Sharp, 2011).

In response to this situation, researchers from the University of Dundee, the Zoological Society of London (ZSL) and Sea-Scope submitted a successful application to the UK's Darwin Initiative in 2012, entitled 'A Sustainable Marine and Fisheries Management Plan for the Pitcairn Islands'. This 3 year project aims to produce a management plan for the coastal waters around Pitcairn which will both preserve ecosystem integrity and guarantee long term economic benefits for the community (Dawson *et al.*, 2013). This research thesis forms part of the Darwin Project's field activities, and will contribute towards providing the necessary data for an effective management plan.

1.5 Aims & Objectives

<u>Aims</u>

- The quantitative description of Pitcairn Island's coastal fish assemblage through data obtained from Baited Remote Underwater Videography (BRUV) sampling.
- The synthesis and application of new data to inform decision-making on Pitcairn Island's marine management and conservation issues.

Objectives

1. The deployment of BRUV frames in Pitcairn Island's coastal waters, sampling a range of sites, depths and habitats.
2. The analysis of BRUV footage in order to assess the species diversity, relative abundance and biomass of the fish assemblage.
3. Setting the BRUV study in context through comparisons with data from previous surveys on Pitcairn Island and BRUV data from French Polynesia.
4. The application of BRUV data to an overall assessment of the health of the fish assemblage, in addition to specific assessments of species which are of importance to fisheries management and conservation.
5. Making informed recommendations for future research and policy action on Pitcairn Island.

This thesis will make a direct contribution to achieving the following indicators and outputs specified in the Darwin Project's proposal (Dawson *et al.,* 2013).

- **Outcome Indicator 2**: 'Fisheries management plans in place for spiny and slipper lobsters, coral trout (yellow-edged lyretail) and other groupers.'
- **Output 1 Indicator 2**: 'Individual fisheries species assessed in a local context'.
- **Output 1 Activity 1.2**: 'Conduct habitat surveys and determine the occurrence and spatial distribution of commercially valued species'.
- **Output 1 Activity 1.3**: 'Conduct biodiversity surveys using standardised approaches that can be compared with other remote island sites'.

1.6 Study Site

Field work was undertaken around the coast of Pitcairn which is located at 25° south and 130° west. The land area spans 450ha with a 9.5km coastline characterised by cliffs and loose rock (Irving & Dawson, 2012). The island is surrounded by a shelf which extends for 300-500m to a depth of around 30m before dropping off (Irving & Dawson, 2012). Pitcairn is not protected by a reef or lagoon and is consequently exposed to large ocean swells. Corals are predominantly absent at less than 10m, possibly due to the combined impact of wave action and soil run off (Sala *et al.,* 2012). Nutrient dissolution into the water column from the soil is a likely explanation for the abundant benthic algae such as *Lobophora* and *Sargassum* spp. at shallow depths (Sala *et al.*, 2012). However, developed coral reefs have been recorded in deeper areas, most prolifically between 10-22m but also beyond 30m (Irving & Dawson, 2012; Sala *et al.,* 2012).

Pitcairn is a challenging marine field work site. The island is inaccessible and remote, and the only reliable way to reach Pitcairn is on the MV Claymore II, a supply ship which visits approximately every 3 months. Field work schedules are consequently inflexible, and with sea passage costing NZ$5000 per passenger, the number of field visits which can be funded within a project budget are limited. Pitcairn's remoteness also increases field work risks as there is no airstrip, the island is out of helicopter range from French Polynesia and evacuation by boat in a medical emergency can take several days.

The weather on Pitcairn can also be disruptive to research schedules, especially as this field work was, by necessity, undertaken during the southern hemisphere winter. With a combination of ocean swells and frequently high winds, rough conditions often prohibit boat-based activities. This issue is exacerbated by the fact that boats can only be launched from 'The Landing', a narrow concrete harbour in Bounty Bay on Pitcairn's northeast coast (Figure 1.2). Thus, when northerly winds and swells predominate it is often impossible for boats to exit the harbour, and there is no alternative access to the sea.

Figure 1.3 The harbour in Bounty Bay (Photo: H. Duffy).

1.7 Thesis Structure

This thesis is set out in the following sections. Firstly the published literature on fish assemblage sampling will be reviewed in Chapter 2, and the key components of the BRUV method will be discussed. The field work and analysis methodology will then be set out in Chapter 3, followed by the results in Chapter 4. Chapter 5 will assess the implications of the results and make future research and policy recommendations based on BRUV data.

Chapter 2: Background & Literature Review

2.1 Fish Assemblage Sampling

In order to obtain quantitative scientific evidence which can support appropriate fisheries management and conservation decision-making, it is important to be able to accurately assess the diversity, abundance, biomass and trophic structure of fish assemblages. Data on these variables can be used as an indicator of fishing pressure, habitat degradation, pollution impact and overall ecosystem health (Dorman *et al.*, 2012). Historically, this information has often been obtained via fisheries-dependent methods such as catch and effort data from commercial fleets (Arreguin-Sanchez & Pitcher, 1997; Rosenberg *et al.*, 2005). Furthermore scientific studies have often directly employed fishing methods such as longlines to sample fish assemblages, particularly when researching larger carnivorous families such as snapper, tuna and shark (Ellis & Demartini, 1992; Brooks *et al.*, 2011).

However, the need for fisheries independent, non-destructive data has been increasingly recognised (Watson *et al.*, 2005). Given the documented depletion of many fish stocks worldwide, and particularly declines of high trophic level species (Worm *et al.*, 2006, Jackson *et al.*, 2001), destructive sampling may clash with management and conservation targets, requiring unsustainably high extraction to achieve sufficient repeat samples (Harvey *et al.*, 2007; Hardinge *et al.*, 2013). Sharks are an example of a group which have historically been sampled destructively, but such methods are increasingly seen as inappropriate due to the mortality involved (Meekan *et al.*, 2006; White *et al.*, 2013), and the threatened status of many species (Worm *et al.*, 2013). Fishing gear sampling also introduces severe biases, particularly with regard to size selectivity and catchability (Hardinge *et al.*, 2013). Therefore, in response to the need for novel fish assemblage assessment methods, underwater cameras have been increasingly employed as a sampling tool (Cappo *et al.*, 2006).

Cameras have been applied to wildlife research since 1902 (Bailey *et al.*, 2009), and underwater cameras have been used in marine studies since the 1940s, initially through still photography before progressing to video images (Hardinge *et al.*, 2013). Earlier remote cameras were used to explore deep habitats inaccessible to SCUBA diving (Sainte-

Marie & Hargrave, 1987; Priede & Merrett, 1996), but they are now widely applied in shallow and mid-water pelagic habitats (Cappo *et al.*, 2006; Santana-Garcon *et al.,* 2014), and are recognised as a valuable non-extractive tool for assessing protected areas, threatened species and scientifically important habitats (Letessier *et al.*, 2013). Furthermore remote cameras have increasingly employed bait to attract species, a technique known as Baited Remote Underwater Videography (BRUV) (Cappo *et al.*, 2006). Studies have found that bait increases sampling power, with baited cameras recording more species and requiring less replicates to detect change compared to cameras deployed without bait (Watson *et al.,* 2005; Harvey *et al.*, 2007).

2.2 Development of BRUV

Earlier BRUV systems used a single horizontal camera, with 'coarse' measurements generated by scale bars or lasers (Cappo *et al.*, 2006). Single cameras can record abundance and diversity (Ellis & Demartini, 1995), however measurements derived from these setups are frequently inaccurate (Cappo *et al.,* 2003) and some studies have been unable to obtain valid measurements with scale bars (Brooks *et al.,* 2011). Horizontal single cameras also cannot standardise the depth of field, an issue which decreases measurement accuracy, and alternative setups which face vertically down onto the bait have been used (Willis *et al.*, 2000). Whilst a vertical setup quantifies the depth of field, the top-down view inhibits accurate measurement or identification and introduces a size selectivity bias because larger species cannot fit beneath the camera (Willis *et al.*, 2000; Cappo *et al.*, 2006).

In order to obtain footage with the power to measure fish accurately, BRUV studies have increasingly employed twin horizontal video cameras which record in stereo, building on earlier research which had already used stereo still photography to measure species such as hammerhead sharks (*Sphyraena* spp.) (Klimley & Brown, 1983). Stereo systems have been proven to generate more accurate measurements compared to single cameras, and have become the standardised setup for baited camera studies (Cappo et al., 2006). Sony HD video cameras or mini camcorders have been commonly used in BRUV studies, but these cameras are large, add considerable weight to a frame and can be prohibitively expensive (Letessier *et al.*, 2013). Recent research has employed GoPro Hero 3 and 3+ cameras as a lighter, cheaper alternative (Figure 2.1) (Letessier *et al.*, 2013; Letessier *et al.*, in prep.). A GoPro setup costs two thirds less than an equivalent Sony HD system, and enables more cameras to be purchased with project funds (Letessier *et al.*, in prep.). This allows more frames to be deployed simultaneously and provides an affordable redundancy in the event of breakage or loss. Concerns have been raised that GoPros might produce less accurate measurements compared to larger cameras, but a recent comparison at the University of Western Australia (UWA) found no significant difference between GoPro and Sony HD error margins, with the slightly lower accuracy of GoPros having 'few ecological implications' (Letessier *et al.*, in prep.). Thus GoPros provide a cost-effective and scientifically robust option for BRUV studies, lowering the financial barrier of field work and potentially facilitating wider implementation of the technique. It should also be noted that GoPros have a wider field of view than Sony HD cameras, a fact which may lead to GoPros yielding higher MaxN values, making the choice of camera a potential factor in abundance data (Letessier, pers. comm., 2014). The wider view of a GoPro also increases the area within which species can be accurately measured, allowing a higher data output from each sample Letessier *et al.*, in prep.).

Figure 2.1 GoPro Hero 3+ cameras with additional battery packs (Photo: H. Duffy).

Another variable within BRUV sampling is the nature and quantity of bait. The suitability of a bait type is primarily determined by moisture content, dispersal area and persistence in the water column (Dorman *et al.*, 2012). Bait must also be economically viable, sustainably harvested and not pose a biohazard risk (Dorman *et al.*, 2012; Clubbe, pers. comm., 2014). Pilchard (*Sardinops* spp.) is commonly used due to its oily flesh which is a more effective and persistent attractant than white-fleshed species or other alternatives (Dorman *et al.*, 2012). The appropriate bait quantity has also been evaluated, and a comparison observed that increasing bait quantity did not significantly affect species attraction, with 200g sufficient to sample a temperate assemblage (Hardinge *et al.*, 2013). However, the ultimate factor determining bait quantity is the composition of the study assemblage, with up to 1000g of bait fully depleted during sampling of a tropical habitat containing abundant carnivores (Hardinge *et al.*, 2013).

Studies have also used different analysis techniques to obtain abundance and length data from video samples. The most common abundance metric in the literature is MaxN (also npeak, MaxNo or NMax) which is obtained by counting the highest number of each species visible at any point in the sample, (Ellis & Demartini, 1992; Langlois *et al.*, 2010; Hardinge *et al.,* 2013). Time In Time Out (TITO) has also been used, but this metric is ineffective when analysing a large, dynamic assemblage (Cappo et al., 2006). MaxN provides a conservative relative abundance estimate which prevents double-counts of individuals which leave and re-enter the field of view (Letessier *et al.*, 2013) and allows diverse, abundant assemblages to be sampled efficiently and accurately when the counting of all individuals is unfeasible (Cappo *et al.,* 2006).

A final advancement in BRUV is the implementation of computer analysis. Stereo cameras allow specialised analysis software to digitally obtain 3D measurements of fish instead of using hardware such as scale bars. SEAGIS EventMeasure, which estimates the position and size of an individual on 3 axes, is widely employed in BRUV analysis and tests have demonstrated that fish can be measured to within 1-2% of actual length (Cappo et al., 2006; Hardinge *et al.*, 2013; Letessier *et al.,* in prep.). This software allows fish to be measured non-invasively, eliminating the need for size data to be obtained destructively. EventMeasure also allows species diversity, MaxN and length data to be collated and exported into text files, streamlining data archiving and facilitating further analysis in other software.

2.3 Comparative Studies Review

In order to assess the validity of BRUV, which is a relatively new addition to marine ecological studies, numerous experiments have tested the technique against extractive sampling techniques (Cappo *et al.*, 2006; Ellis & Demartini, 1995; Brooks *et al.,* 2011, Langlois *et al.,* 2012).

As previously discussed, long lining has been commonly used as an assessment tool for species diversity and abundance estimates, whilst BRUV provides a non-destructive option which reduces negative environmental impacts (Cappo et al., 2006). A 1995 comparison found that a BRUV sampling programme recorded 94 species, with 54 caught on longlines in the same habitat, thus indicating that BRUV sampled a greater proportion of the fish assemblage (Ellis & Demartini, 1995). Furthermore analysis of bait consumption found that longlining required 1227kg of bait compared to 84kg for the equivalent number of BRUV samples (Brooks *et al.*, 2011). In addition BRUV cost two thirds less than longlining whilst generating similar abundance estimates (Brooks *et al.,* 2011). In a third comparison BRUV generated similar length-frequency distributions to longlines (Langlois *et al.,* 2012). Therefore BRUV is preferable to longlining in terms of sampling power, bait sustainability, cost efficiency and impact of sampling on the study ecosystem.

BRUV has also been compared to fish traps, which offer an alternative extractive sampling approach (Harvey *et al.,* 2012). BRUV detected 91 species compared to 30 in the traps, and proved to be a more powerful technique for assessing diversity, abundance, length distributions and temporal variations (Harvey *et al*., 2012). Overall, research has shown that BRUV is a preferable alternative to common extractive sampling approaches when assessed against a number of criteria.

However, several alternative non-extractive methods also exist, primarily utilising SCUBA divers. In shallow water environments, Underwater Visual Census (UVC) by SCUBA divers has been a predominant method (Cappo *et al.,* 2003). However, the validity of UVC can be undermined by inter-observer variability in identifying species, estimating abundance and transect swimming speed (Watson *et al*., 2005). Diver Operated Video (DOV) eliminates inter-observer variability by allowing divers to record fish using handheld stereo cameras, with the footage later reviewed for species diversity and abundance (Watson *et al*., 2005; Langlois *et al.,* 2010; Letessier *et al.*, 2013). However, a limitation of any SCUBA methodology is the heterogeneity of fish behavioural responses to divers, which can bias abundance estimates (Langlois *et al*., 2010). Species in fished areas may exhibit avoidance behaviour and thus be underestimated by divers, especially if the species is targeted by spear fishermen (Meekan *et al.*, 2006; Watson *et al.,* 2010). Evidence for this behavioural response is substantial for carnivores such as grouper and shark, in addition to large herbivores such as parrotfish, thus making divers a potentially inappropriate sampling approach for these critical indicator species (Watson *et al*., 2005) . Baited cameras also increase the power to sample cryptic carnivores which might otherwise remain hidden from diver sampling (Watson *et al.,* 2010). However, it has been suggested that baited cameras may overestimate carnivore abundance and underestimate herbivores or corallivores (Cappo *et al.*, 2006). In order to resolve these uncertainties, BRUV has been directly compared to other non-extractive methods.

In two comparisons between DOV and BRUV carried out at UWA, BRUV detected higher species richness in both cases (Langlois *et al.*, 2010; Watson *et al.*, 2010). Neither study found that BRUV sampled fewer herbivores than DOV, and BRUV also had greater power to detect fish assemblage variation. Furthermore BRUV recorded equal or higher values for all assemblage analysis parameters (Langlois *et al.*, 2010; Watson *et al.*, 2010). Indeed many herbivores and corallivores are not 'obligate' feeders and will scavenge bait opportunistically (Letessier, pers. comm., 2014). Moreover, studies have found that activity around the bait may stimulate non-carnivorous species to approach even if they are not attracted by the bait itself, a phenomenon described as a 'sheep effect' (Watson *et al.*, 2005; Watson *et al.*, 2010). Intraspecific social behaviours, sheltering behaviour and predatory behaviour have also been observed to cause individuals to approach the cameras (Dorman *et al.*, 2012). These heterogeneous behavioural responses may explain why BRUV appears not to underestimate herbivores and corallivores, despite only providing a direct feeding incentive for carnivores.

Further advantages of BRUV over SCUBA sampling are also acknowledged. Cost-benefit analysis found BRUV to improve efficiency and cost effectiveness, with DOV estimated to require 299 hours of field time to achieve the equivalent sampling coverage of 89 hours of BRUV (Langlois *et al.*, 2010). In addition BRUV does not require SCUBA divers, thus minimising anthropogenic disturbance, reducing the need for onsite specialists and eliminating the risks associated with SCUBA (Langlois *et al.*, 2010). BRUV is also unaffected by the depth restrictions which limit SCUBA surveys, particularly in remote locations without decompression facilities, thus allowing greater flexibility and spatial coverage (Koldewey, pers. comm., 2014). In summary, BRUV sampling is statistically powerful, efficient and repeatable across spatial and temporal scales whilst mitigating some of the biases of other techniques.

2.4 BRUV Limitations

Despite the advantages of BRUV, certain biases and limitations remain. Baited sampling is limited by an inability to quantify bait plume dispersal, even though basic models have been constructed to predict plume movement and the distance over which fish are attracted (Wolfram, 2012). These models may be valid in the deep sea (Sainte-Marie & Hargrave, 1987) but their assumptions are violated by dynamic shallow environments with constantly moving species and high food availability (Hardinge *et al.*, 2013). Bait plume quantification is further complicated by the first feeding individuals which macerate the bait, causing 'chumming' which may accelerate dispersal (Dorman *et al.*, 2012). Therefore, plume dispersal remains an unknown 'confounding' factor in BRUV, with sampling areas impossible to estimate (Cappo *et al.*, 2003; Letessier *et al.*, 2013). Due to this uncertainty, BRUV only provides a relative abundance estimate (Meekan *et al.*, 2006), and distances of 200-300m between concurrent samples are recommended to ensure independence (Dorman *et al.*, 2012).

A further issue in BRUV sampling is a reliance on sufficient visibility for species to be identified and measured accurately (Cappo *et al.*, 2006; Watson *et al.*, 2010). When particles or debris are suspended in the water column, video analysis may be impossible. Furthermore accurate identification has proved problematic in BRUV studies of sharks, with video insufficiently clear to discern subtle morphological differences between species (Brooks *et al.*, 2011).

The use of MaxN as an abundance measure for BRUV also introduces a potential bias. Whilst MaxN prevents double counting and the overestimation of abundance, it generates a conservative relative abundance value which may instead lead to underestimation, particularly for those species which approach the bait in large schools (Letessier, pers. comm., 2014). In addition, the extensive data archiving and analysis required by BRUV research has been identified as the technique's 'greatest expense and bottleneck', with each hour of footage requiring up to 3-4 hours of study which can lead to observer fatigue (Cappo et al., 2006).

The logistical requirements of BRUV, with frames commonly lowered from and hauled back to a boat using ropes, can also be problematic. For deep deployments or in areas of strong current the ropes present a hazard which may entangle in the boat or cause the frame to drag on the seabed. Consequently the need for alternative recovery methods such as remotely activated pony bottles or lift bags has been emphasised (Cappo *et al.,* 2006). However, such additions are expensive compared to line hauling, and would increase the cost of a sampling programme.

Chapter 3: Materials & Methods

3.1 Methodological Framework

Given the recognised need for new quantitative data on the Pitcairn Island fish assemblage, and the importance of causing minimal environmental impact during sampling, BRUV was selected as the core component of the methodology. To date Pitcairn's coastal fish populations have only been assessed via extractive techniques (Ake-Gotesson, 2012) or SCUBA observation (Sala *et al.*, 2012; Irving & Dawson, 2012) and therefore this methodology represents the first application of a baited camera approach at the study site. Analysis of BRUV footage with SEAGIS EventMeasure software allowed the fish assemblage to be quantified across several metrics, maximising data output from field work.

The purpose of comparison with the Tuamotu Islands was to contextualise Pitcairn's fish assemblage on a regional scale, taking advantage of the inter-site comparability facilitated by standardised BRUV methodologies. The Tuamotus are situated in the extreme east of French Polynesia and are the nearest westward island group to the Pitcairn Islands, containing a number of uninhabited and 'pristine' coral atolls (Letessier, pers. comm., 2014). Thus the Tuamotu group provides a reference point for comparatively assessing both biogeographical trends and fishing impact. Raw BRUV data from the Tuamotus was provided for analysis in this thesis by researchers from IRD.

3.2 Equipment

Five BRUV frames were assembled upon arrival on Pitcairn Island in May 2014. The construction of multiple frames allowed up to 10 BRUV deployments on each boat trip, maximising the efficiency of sampling time. The setup was a continuation of a design which has been widely employed for seabed based stereo-video studies (Langlois *et al.*, 2010; Letessier *et al.*, in prep.), and an aluminium frame was used, measuring 1255x694cm at the base.

Two GoPro Hero 3+ cameras (with additional batteries) were placed inside waterproof housings mounted 800mm apart on a steel bar, with both housings pre-calibrated in a pool at UWA to a convergence angle of 8 degrees. The use of two cameras calibrated in fixed positions allowed stereo footage to be filmed, a requirement for accurate measurements (Cappo *et al.*, 2006). 18 GoPro cameras were used in order to maximise the number of deployments per boat outing, in addition to providing spares in the event of breakage or loss. The housings bar was attached with the cameras facing forwards out of the frame, and a 1.6m plastic bait arm was fixed perpendicular to the bar, with a 260x180 cm wire mesh bait bag fastened on the end. A rope and buoy were attached to each frame, with 30m, 40m and 55m ropes used according to target depth (Figure 3.1). Pilchard (*Sardinops sagax*), was selected as bait and sourced from a New Zealand fishing company (Letessier, pers. comm., 2014) with all bait kept frozen until use. Imported fish was the most appropriate bait choice, as obtaining sufficient quantities from Pitcairn's waters would have contradicted conservation objectives in addition to being logistically unfeasible. Pilchards have been commonly used in BRUV work, and bait standardisation is essential for ensuring inter-study comparability (Dorman *et al.*, 2012; Langlois *et al.*, 2010; Hardinge *et al.*, 2013; Letessier *et al.*, 2013).

Figure 3.1 A completed BRUV frame on Pitcairn Island (Photo: H.Duffy).

Prior to deployment the bag was filled with 600g of pilchards, with each fish broken up and crushed (Figure 3.2). This presentation ensured dispersal of attractant into the water but also guarded against premature depletion by retaining chunks. Previous studies indicate that appropriate bait quantity is dependent on the study assemblage, and 600g was deemed a sufficient quantity given the evidence for high fish biomass on Pitcairn (Hardinge *et al.*, 2013; Letessier, pers. comm., 2014).

Figure 3.2 Presentation of bait (Photo: R. Irving).

3.3 Sampling Strategy

The sampling programme aimed to deploy BRUV frames around the coastline of Pitcairn Island across a depth range of 10-40m. Diver transect sites from National Geographic's expedition were used to guide the spatial coverage of deployments (Sala *et al.*, 2012), and local site names were used to designate new sampling locations (Figure 3.3).

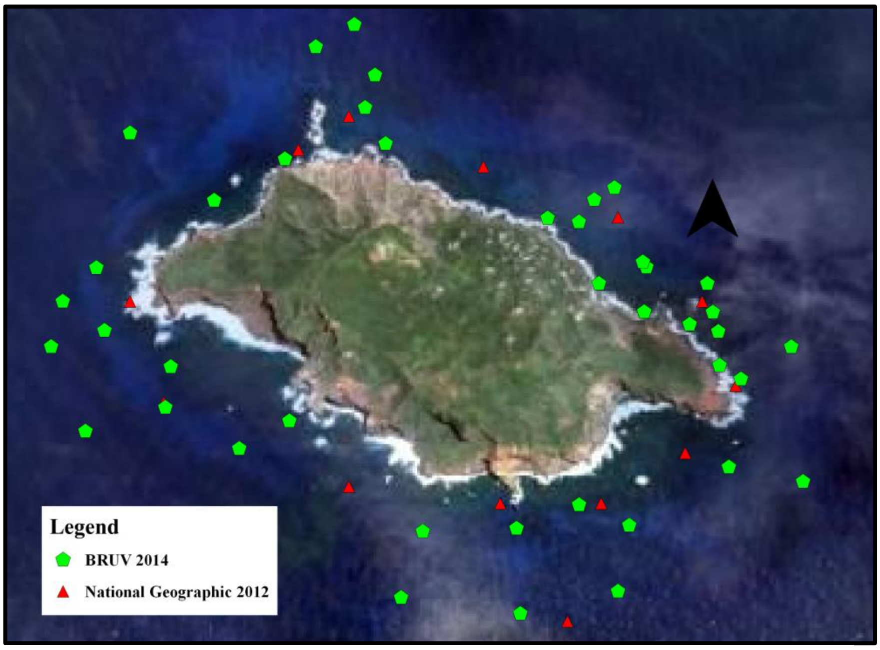

Figure 3.3 Map of Pitcairn Island showing the distribution of BRUV sampling sites. The sites sampled by National Geographic's SCUBA transects are also indicated (Sala *et al.*, 2012; Friedlander, pers. comm., 2014).

In order to facilitate comparisons between depths, deployments were targeted within three categories of <15m, 15-25m and >25m. Deployments aimed to cover all three categories at each sampling site, but it was also necessary to seperate concurrent deployments by at least 300m. This precaution reflects the recommendations made to guarantee sample independence in light of unknown bait dispersal (Harvey *et al.*, 2007; Langlois *et al.*, 2010; Dorman *et al.*, 2012; Hardinge *et al.*, 2013). At times it was necessary for deployments to be opportunistic in order to ensure both sample independence and target depth. At some locations it was impossible to sample at less than 15m deep because finding the depth required deployment too close to the shoreline, risking boat damage and rope entanglement.

3.4 Deployment

Figure 3.4 Deploying a BRUV frame from the longboat (Photo: R. Irving).

BRUV frames were deployed from the Pitcairn Island longboat with assistance from a speedboat (Figure 3.4). On occasion it was necessary to deploy frames solely from the speedboat due to longboat unavailability. Upon arrival at a sampling site, a handheld depth sounder was deployed from the speedboat to locate the target depth. The frame was then lowered onto the seabed and checked to ensure it had landed upright with the bait arm horizontal. A GPS was used to mark deployment location, and the cameras were left to record for a one hour sampling period. Frames were recovered either by hand hauling or a pulley, depending on depth and sea conditions. Multiple frames were deployed consecutively on each boat trip, and the GPS was used to check the distance between samples. If a frame was deployed twice in one boat trip then bait was replenished to ensure consistency. The cameras had sufficient battery life to record two samples without recharging or replacement.

3.5 Video Analysis

In order to make the footage compatible with analysis software, Xilisoft Video Converter was used to convert the raw videos from MPE4 to avi. SEAGIS EventMeasure, a recognised analysis tool for stereo BRUV (Cappo *et al.*, 2006; Dorman *et al.*, 2012; Hardinge *et al.*, 2013; Letessier *et al.*, 2013), was used to obtain diversity, abundance and individual length data.

<u>3.5.1 Diversity & Abundance</u>

In order to quantify a sample's diversity, each species was marked upon first appearance, and the MaxN of every species was recorded. The point at which any species first fed on the bait was also marked. Individuals identified to family or genus level were also recorded and assigned a MaxN value. When individuals of the same genus or family appeared simultaneously and could not be distinguished to species level, their MaxNs were merged. In order to count large schools which approached the bait, MaxN was computed by marking each visible fish (Figure 3.5)

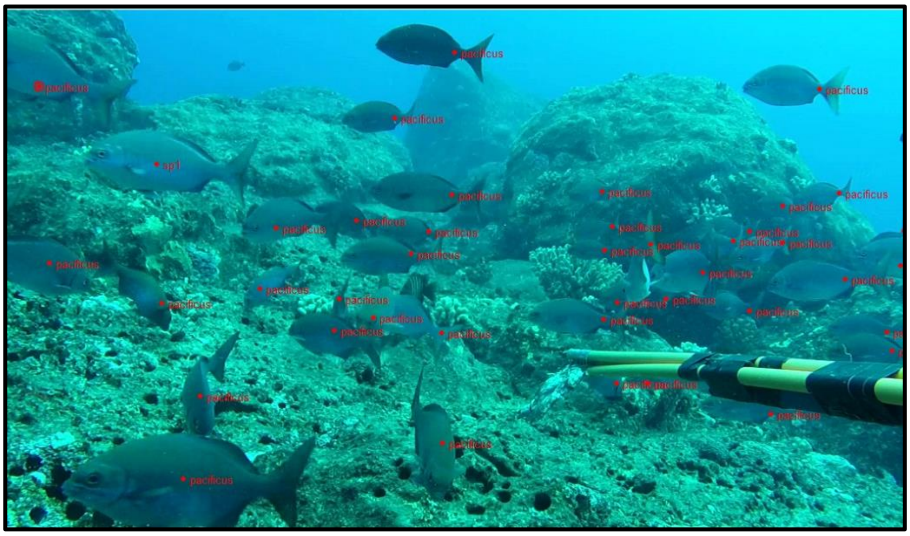

Figure 3.5 Marking individuals to count gray drummer (*Kyphosus pacificus*) (Photo: H. Duffy).

When a school passed at a distance an approximate subset was counted and multiplied to estimate MaxN (Groves, pers. comm., 2014). All identifications and MaxN values were obtained using footage from the frame’s left camera. The sampling period began as soon as the frame landed on the seabed (after adjustments), and exactly an hour of video was analysed. A still image from the start of each sample was used to classify habitat using rock, algae, sand, and coral categories which allowed the heterogeneity of Pitcairn’s coastal habitats to be taken into account (Sala *et al.,* 2012; Irving & Dawson, 2012). Classifications were based on the habitat type which was observed to cover the highest percentage of the visible substrate.

3.5.2 3D Measurements

The second stage of EventMeasure analysis involved obtaining 3D fork length measurements of individuals by viewing footage from the left and right cameras in stereo. Before taking measurements from a sample, individual CAM files were loaded to calibrate the software and maximise measurement accuracy according to the calibration of the housing setup (Letessier, pers. comm., 2014). Fish were only measured if their bodies were straight, side-on and fully visible on both cameras (Figure 3.6).

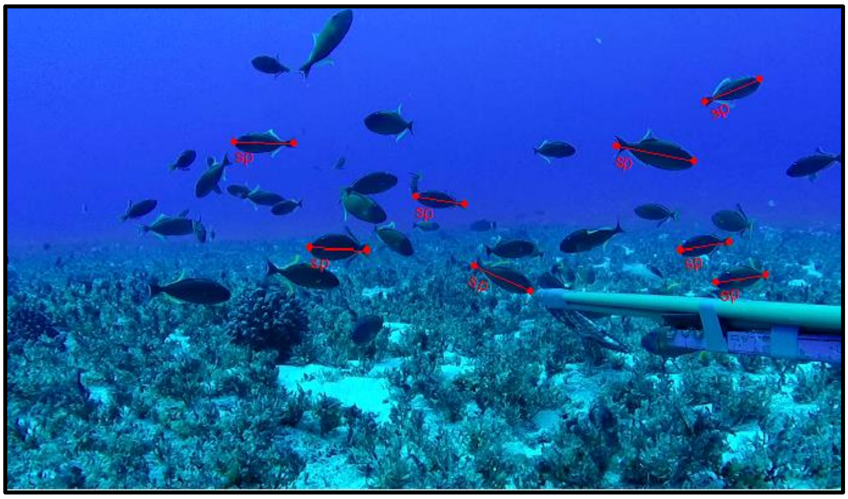

Figure 3.6. Measuring individual crosshatch triggerfish (*Xanthichthys mento*). Only left camera shown (Photo: H. Duffy.

A measurement was accepted if the precision value generated by EventMeasure was less than 10% of the individual's computed fork length, based on the recommendation that measurements with precision values above this threshold should be discarded (Groves, pers. comm., 2014). In addition, a measurement was only deemed accurate if EventMeasure estimated the individual to be 5m or less from the camera, in light of observed inaccuracies in measurements at greater distances (Langlois *et al.*, 2010; Letessier *et al.,* in prep.). Length data were also checked against known fork length ranges of species, and any measurements substantially outside known size range were discarded before re-measuring the individual (Allen *et al.*, 2007; Lieske & Myers 1996; Fishbase, 2014). In order to avoid the repeat measurement of a returning individual, measurements were only taken from the point of species MaxN. If no valid measurements could be obtained from the point of MaxN, an alternative frame was used when possible.

3.6 Biomass

Measurements were averaged for each species to produce mean fork length values. Stated common lengths were used for species not measured during this study (Fishbase, 2014; Allen *et al.*, 2007). Individual weight estimates were obtained using the length-weight relationship $W = aL^b$ where L is the mean length and W is the weight estimate. Species-specific a and b values were obtained from published length-weight studies or models (Fishbase, 2014). Individual weights were multiplied by the total MaxN for the species to estimate overall assemblage biomass. Individuals identified to family or genus level were included in biomass calculations, with length and weight values based on morphologically and phylogenetically similar species. If length-weight relationships were unavailable for an identified species, biomass was estimated with parameters of other species in the genus. Top predator biomass in the Tuamotu Islands was estimated with the same methodology (see section 3.7).

3.7 Tuamotu Islands Comparison

BRUV results from Pitcairn were compared to raw data from a BRUV study carried out across ten atolls in the Tuamotu Islands (French Polynesia) by L'Institut de recherche pour le développement (IRD) in 2013. Raw cumulative values were not comparable due to differing spatial scales and sampling effort, so mean values for species richness, abundance and biomass were used for statistical analysis. Pitcairn data was initially compared to overall mean values from all Tuamotu samples, and then compared to island-specific mean values. Variation in means was analysed across a longitudinal gradient to investigate biogeographical patterns (Longhurst, 1998), and the means of inhabited and uninhabited islands were compared. Only large carnivore (trophic level >3.5) measurements were available from the Tuamotu samples (Juhel, pers. comm., 2014), and thus assemblage biomass was not calculated.

3.8 Statistical Analysis

All EventMeasure data were collated in Microsoft Excel and all statistical analysis was carried out in R Studio software (version 0.98.507). The additional 'vegan' R package was used to plot species accumulation ('specaccum' function') and to extrapolate total species richness values ('specpool' function) using 'jack1', 'boot' and 'chao' richness estimation indexes (Oksanen, 2013).

Chapter 4: Results

4.1 Summary of Sampling & EventMeasure Analysis

Forty-two BRUV deployments were completed between 30th May and 21st July 2014, of which 39 produced valid samples. One deployment landed vertically and could not be analysed, and on two deployments the cameras were set incorrectly and did not record. Deployment depths ranged from 7m to 33m and the mean depth sampled was 19.24m (±7.39 standard deviation) (Figure 4.1). Algae and rock-dominated habitats were most commonly sampled, accounting for 38.46% & 33.33% of habitat classifications respectively, whilst coral and sand accounted for 15.38% and 12.82% of classifications (Figure 4.2).

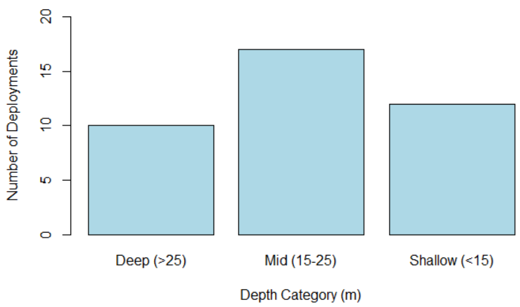

Figure 4.1 Distribution of sampling effort across the 3 targeted depth categories.

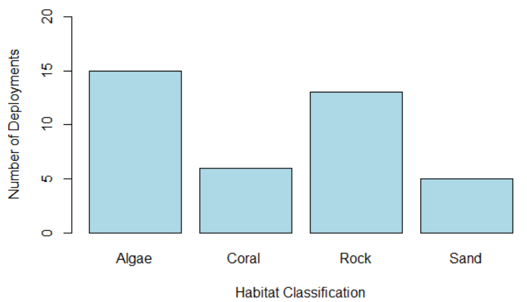

Figure 4.2 Distribution of sampling effort across the four primary habitat types.

A total of 658 MaxN values were obtained from EventMeasure analysis of video samples. 49.32% of MaxN values were obtained within the first 15 minutes of sampling, and the mean time of MaxN was 20.79 minutes (±17.87 sd.) (Figure 4.3). 76.92% of samples contained feeding behaviour and 21 species fed on the bait, with crosshatch triggerfish feeding on 38.46% of samples, the highest proportion for any species. First feeding (for each species per sample) occurred at a mean time of 21.19 minutes (±17.65 sd.), and 47.73% of first feeding observations occurred in the first 15 minutes of sampling (Figure 4.4).

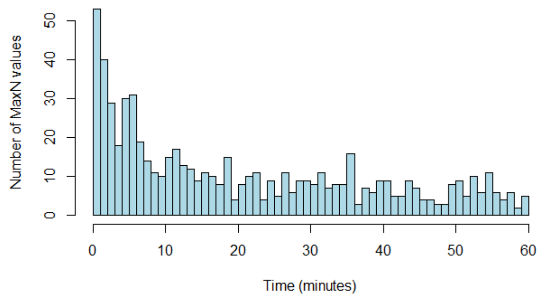

Figure 4.3 Temporal spread of MaxN values across all sampling periods.

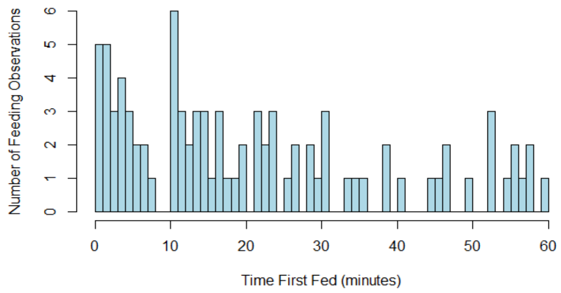

Figure 4.4 Temporal spread of first feeding observations across all sampling periods

2769 fish from 26 families were sampled, 88 species were identified and 94.51**%** of individuals were identified to species level, with 3.39% and 2.09**%** identified to family and genus level respectively (see Appendix I for species list). The most diverse sample recorded 33 species, the least diverse recorded just 3 species, and mean species richness per sample was 17.28 (±7.25 sd.). Abundance values ranged from 198 to 11, and mean abundance per sample was 70.89 (±43.84 sd.).

Fork length measurements were obtained from 37 deployments, and 484 measurement values for 57 species were computed at 5m or less. The largest measurement obtained was a 1.62m giant trevally *(Caranx ignobilis)* and the smallest was a 40.66mm vanderbilt's chromis *(Chromis vanderbilti)*.

4.2 Depth Analysis

Spearman's Correlation Coefficient was initially used to assess the effect of sampling depth (uncategorised) on abundance and species richness, with both relationships observed to be non-linear and non-Gaussian in distribution. A significant but weak correlation was found between depth and abundance (Spearman's rho = 0.22, p = 0.18), and a significant correlation was not observed between depth and species richness (Spearman's rho = -0.047, p = 0.77). The variance of species richness between the three depth categories was tested using ANOVA, and significant variance in means was not observed (p >0.07). In light of non-normal residuals, the variance in abundance between depth categories was analysed with a Kruskal-Wallis test which indicated a weakly significant relationship (K-W χ^2 = 1.49 , p = 0.47) (Figure 4.5, Figure 4.6).

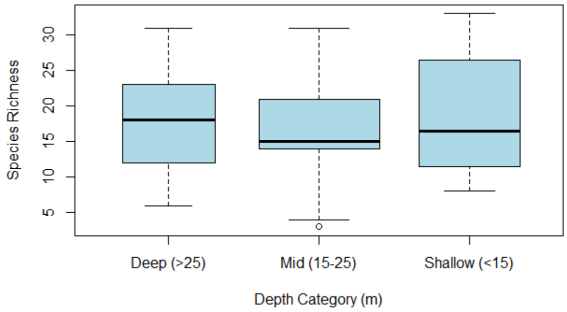

Figure 4.5 Range of species richness values within the three sample depth categories.

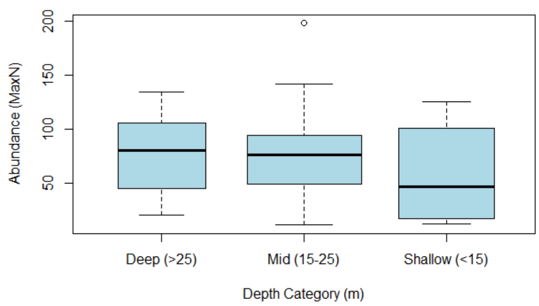

Figure 4.6 Range of abundance (MaxN) values within the three sample depth categories.

4.3 Habitat Analysis

Coral habitats supported the highest species richness and abundance, with mean richness of 26.83 (±4.83 sd.) and mean abundance of 103.8 **(**±28.49 sd.). Sand habitats supported the lowest species richness and abundance, with mean richness of 7 **(**±4.36 sd.) and mean abundance of 52.4 **(**±55.53 sd.) (Figure 4.7, Figure 4.8).

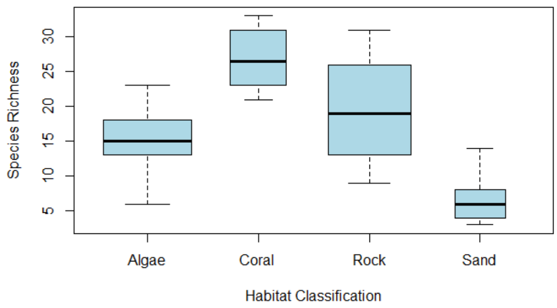

Figure 4.7 Range of species richness values recorded within each habitat classification.

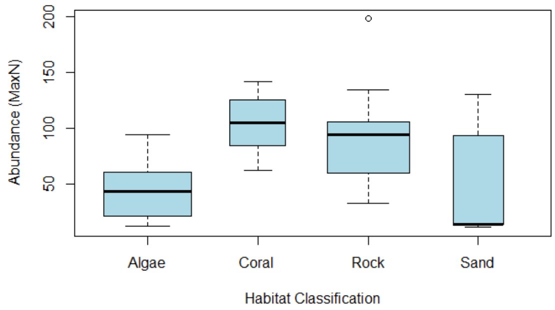

Figure 4.8 Range of abundance (MaxN) values recorded within each habitat classification.

ANOVA results indicated a strongly significant variance in mean species richness between habitat types (p <0.0001). Species richness did not vary significantly between rock habitats and algae habitats (t = 1.99, p = 0.54), but significantly higher richness was observed in coral habitats (t = 4.27, p <0.0002). The ANOVA also observed significantly lower richness in sand habitats (t = -2.74, p <0.01). A Kruskal-Wallis test indicated significant variance in mean abundance between habitat types (K-W χ^2 = 15.42, p <0.01), with non-normal residuals observed.

4.4 Species Richness Extrapolation

The 88 species identified during sampling were plotted on a species accumulation curve, and the total species richness of the assemblage was extrapolated using three estimation indices (Oksanen, 2014). These indices produced estimated species richness values ranging from 99.7(±22.92 sd.) to 132 (±8.89 sd.) (Figure 4.9).

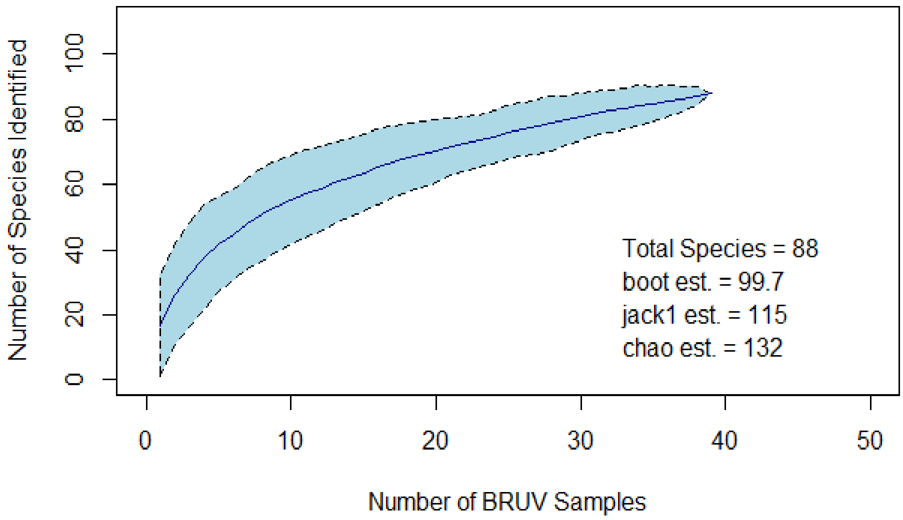

Figure 4.9 Curve showing the accumulation of identified species during sampling (dark blue line). Confidence intervals are indicated by the light blue polygon and dotted lines. Values for estimated total species richness according to three indices are inset.

4.5 Fish Assemblage Characteristics

The fish assemblage was dominated by gray drummer (*Kyphosus pacificus*) and crosshatch triggerfish (*Xanthichthys mento*) which accounted for 23.69% and 28.02% of total MaxN respectively. The next highest MaxN value for a single species was recorded by red and green coris (*Coris roseoviridis*), a regional endemic which accounted for 4.62% of total MaxN. Scythe triggerfish (*Sufflamen bursa*) was the most widespread species, recorded on 84.61% of samples (Table 4.1).

Table 4.1 Summary of key data indices for the most common species (in terms of relative abundance) in each of the main fish families recorded on Pitcairn.

Family	Common Name	Scientific Name	Total MaxN	% Total Abundance	% Total Biomass	% Samples Recorded
Acanthuridae	Whitebar surgeonfish	*Acanthurus leucopareius*	34	1.23	0.55	38.46
Balistidae	Crosshatch triggerfish	*Xanthichthys mento*	776	28.03	8.59	53.84
Carangidae	Island trevally	*Carangoides orthogrammus*	16	0.57	2.49	30.77
Chaetodontidae	Yellowback butterflyfish	*Chaetodon mertensii*	62	2.24	0.36	58.97
Kyphosidae	Gray drummer	*Kyphosus pacificus*	656	23.69	19.33	46.15
Labridae	Red and green coris	*Coris roseoviridis*	128	4.29	0.095	66.67
Lutjanidae	Blue lined snapper	*Lutjanus kasmira*	9	0.36	0.41	20.52
Mullidae	Multi-barred goatfish	*Parupeneus multifasciatus*	53	1.92	0.92	64.11
Pomacentridae	Vanderbilt's chromis	*Chromis vanderbilti*	70	2.53	0.096	5.12
Scaridae	Highfin parrotfish	*Scarus longipinnis*	18	0.65	0.85	23.07
Serranidae	Blacktip grouper	*Epinephelus fasciatus*	59	2.13	1.76	58.97

4.6 Biomass & Trophic Structure

The sampled biomass was estimated at 1381.15kg, with mean biomass per sample of 35.14kghr. Herbivores (trophic level 2.0-2.9) accounted for 48.66% of biomass, whilst planktivores and small carnivores (trophic level 3-3.9) and top predators (trophic level >= 4) accounted for 23.12**%** and 28.31% respectively (Figure 4.10).

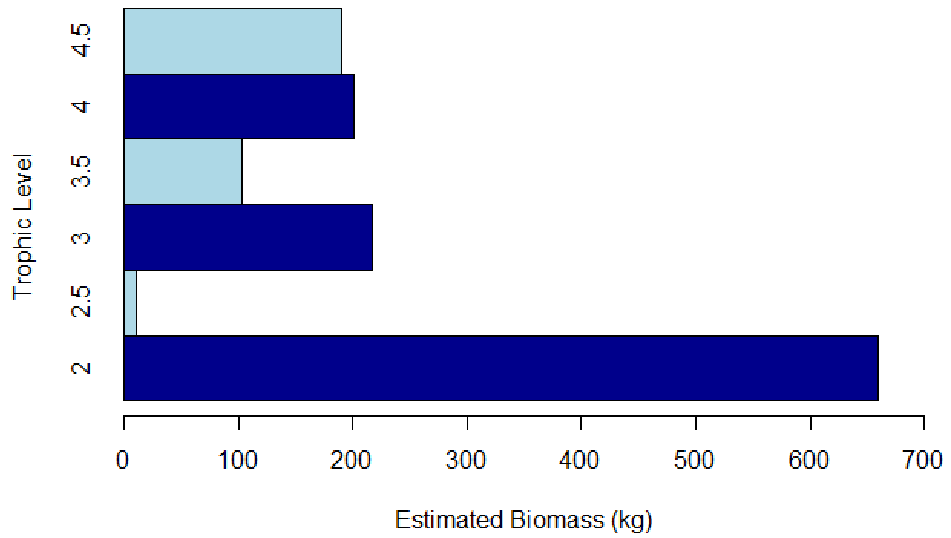

Figure 4.10 Pyramid showing fish assemblage trophic structure in terms of estimated biomass, with biomass summed from all samples and binned by half trophic levels.

Gray drummer recorded the highest species biomass and accounted for 19.33% of total assemblage biomass. This species also accounted for 39.79% of herbivore biomass, followed by 37.64% bluespine unicornfish (*Naso unicornis*) and 1.74% highfin parrotfish (*Scarus longipinnis*). Crosshatch triggerfish accounted for 37.19% of small carnivore and planktivore biomass, followed by 10.34% blue triggerfish (*Pseudobalistes fuscus*) and 7.64% blacktip grouper (*Epinephelus fasciatus*). Giant trevally (*Caranx ignobilis*) accounted for 16.53% of top predator biomass, followed by 11.08**%** yellowtail amberjack (*Seriola lalandi*) and 10.45**%** unidentified tuna (*Thunnus* sp.). In the case of both giant trevally and unidentified tuna only one individual was observed. A single grey reef shark (*Carcharhinus amblyrhyncos*) accounted for a further 4.99% of top predator biomass.

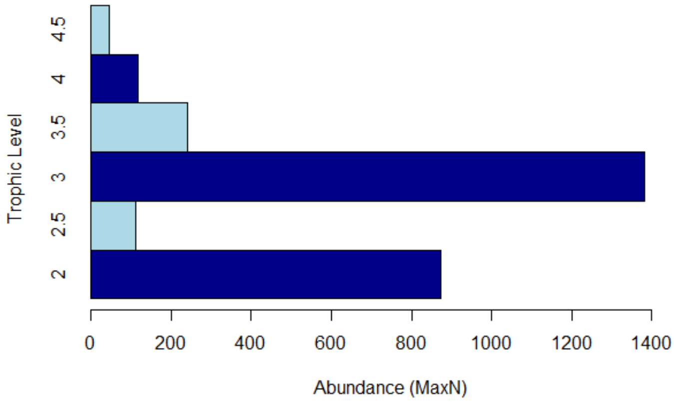

Figure 4.11 Pyramid showing fish assemblage trophic structure in terms of abundance, with MaxN values binned by half trophic level.

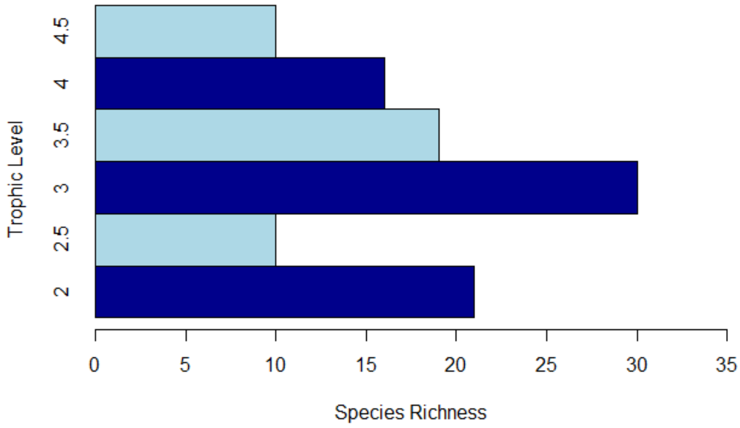

Figure 4.12 Pyramid showing fish assemblage trophic structure in terms of species richness, with species binned by half trophic level.

The trophic structure of the assemblage was also plotted in terms of abundance and species richness (Figure 4.11, Figure 4.12). Planktivores and small carnivores (trophic level 3-3.9) were the most diverse and most abundant group, accounting for 43.69% of species richness and 57.58% of abundance respectively. Top predators (trophic level 4-4.5) accounted for 24.52% of species richness and 5.85% of abundance, whilst herbivores (trophic level <3) accounted for 29.24% of species richness and 35.53% of abundance.

4.7 Target Species

130 measurements were obtained for the three reef species identified by SPC as potential commercial targets (Sharp, 2011), and a further 30 measurements were obtained for reef species identified as subsistence and sport fishing targets on Pitcairn (Table 4.2) (Ake-Gotesson, 2012, Brown, D., *pers. comm.* 2014., Christian, B., pers. comm.,2014).

Table 4.2 Summary of measurement data for key fisheries species. Common lengths obtained from Fishbase.

Common Name	Scientific Name	Number of Measurements	Mean Length (mm)	Common Length (mm)
Gray drummer	*Kyphosus pacificus*	98	287.31 (±45.91)	286
Island trevally	*Carangoides orthogrammus*	10	499.09 (±123.96)	400
Black trevally	*Caranx lugubris*	7	413.81 (±63.16)	700
Clown coris	*Coris aygula*	7	457.76 (±215.55)	437.5
Blacktip grouper	*Epinephelus fasciatus*	23	298.32 (±58.75)	220
Yellow-edged lyretail	*Variola louti*	9	501.68 (±99.66)	750

Depth and habitat specificity of the SPC's target species (gray drummer, blacktip grouper and yellow-edged lyretail) was examined graphically and evaluated using Kruskal-Wallis one-way analysis of variance tests (Figure 4.13, Figure 4.14, Table 4.3). The abundance of all three species was not significantly affected by depth category, and only gray drummer abundance varied significantly with habitat type

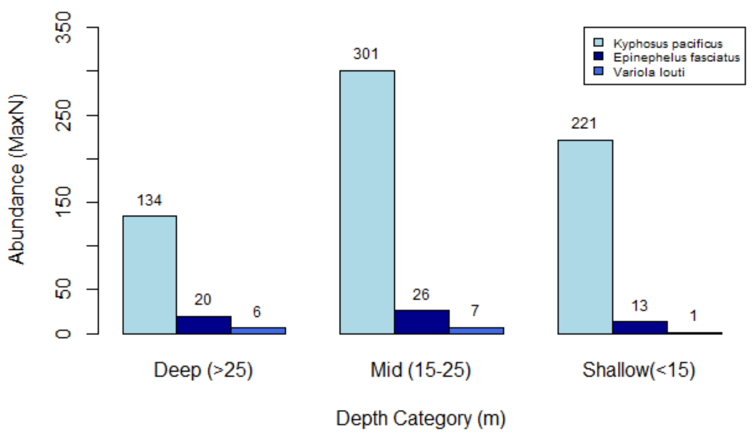

Figure 4.13 Abundance of SPC's proposed commercial target species across sampling depth categories.

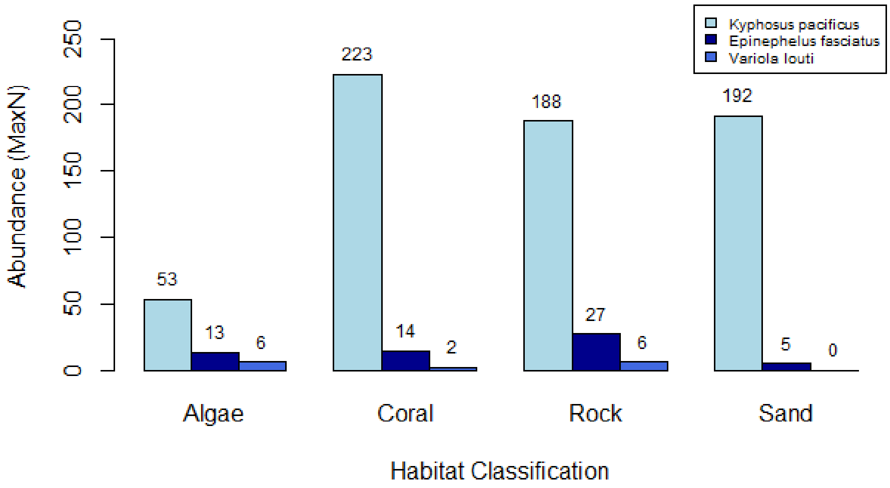

Figure 4.14 Abundance of SPC's proposed commercial target species across habitat types.

Table 4.3 Results of Kruskal-Wallis one way analysis of variance tests for the effect of depth category and habitat type on the relative abundance (MaxN) of SPC's proposed commercial target species.

Species	Kruskal-Wallis Result: Depth Category	Kruskal-Wallis Result: Habitat Type
Gray drummer (*Kyphosus pacificus)*	K-W χ^2 = 0.56, p = 0.75	K-W χ^2 = 11.25, p <0.02
Blacktip grouper (*Epinephelus fasciatus)*	K-W χ^2 = 1.52, p = 0.47	K-W χ^2 = 6.62, p >0.08
Yellow-edged lyretail (*Variola louti).*	K-W χ^2 = 5.89, p = 0.052	K-W χ^2 = 2.56, p = 0.46

4.8 Top Predators

The abundance (of top predators (trophic level >= 4) was also plotted across depth categories and habitats (Figure 4.15, Figure 4.16). The highest MaxN for the trophic group was 8, and the mean abundance of top predators per sample was 4.17 (±2.25 sd.).

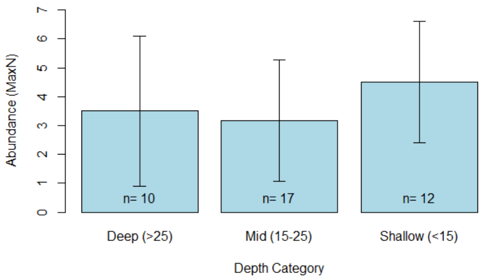

Figure 4.15 Abundance of top predators across sampling depth categories.

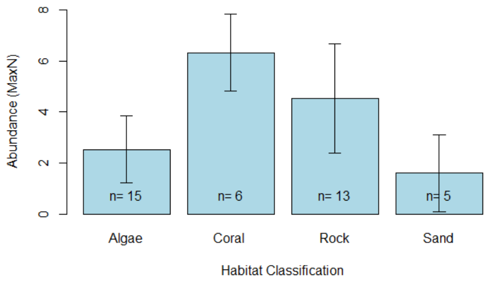

Figure 4.16 Abundance of top predators across habitat types.

Kruskal-Wallis tests on the effects of habitat and sample depth category on top predator abundance indicated a strong positive relationship between habitat type and abundance (K-W χ^2 = 18.07, p <0.001, with the effect of depth category on abundance observed t to be significant but weak (K-W χ^2 = 2.37, p = 0.31). The relationship between abundance and depth (uncategorised) was further analysed with a Spearman's rank correlation test, which indicated a weak negative correlation (Spearman's rho = -0.15, p = 0.38).

4.9 Comparison: Pitcairn & Tuamotu Islands

4.9.1 Two Sample Analysis

Table 4.4 Summary of key statistics from the BRUV sampling programmes on Pitcairn Island and the Tuamotu Islands.

	Pitcairn Island	Tuamotu Islands
Number of Deployments	39 (1 island)	52 (10 atolls)
Deployment Depth Range (m)	7-33	5-55
Mean Deployment Depth (m)	19.24(±7.39 sd.)	12.35(±6.37 sd.)
Total Species Recorded	88	170
Mean Species Richness per Sample	17.28 (±7.25 sd.)	31.38 (±8.84 sd.)

Range of Species Richness Values	3-33	9-48
Mean Abundance per Sample (MaxN)	70.89 (±43.84 sd.)	228.7(±126.38 sd.)
Range of Abundance Values (MaxN)	11-198	24-520
Mean Top Predator Biomass per Sample (kg)	10.14	48.04

Summary indices from the two BRUV programmes were initially compared using a Welch Two Sample t-test (in light of unequal variance) and a highly significant result was observed for both mean species richness ($p < 0.0004$) and mean abundance (MaxN) per sample ($p < 0.0005$). A further Welch t-test also indicated significant variation in the mean abundance (MaxN) of top predators per sample ($p < 0.0002$).

4.9.2 Inter-Island Analyses

Mean values per island for species richness, abundance and top predator biomass were plotted across a longitudinal gradient (Figure 4.16, Figure 4.17, Figure 4.18). A significant relationship between the longitude of each island and mean species richness values was indicated by a Generalized Linear Model (GLM) ($t = 4.25$, $p < 0.003$) utilising a quasi-Poisson distribution. However, GLM analysis did not find longitude to have a significant effect on mean abundance or mean top predator biomass ($p > 0.05$). The effect of longitude on species richness was further explored by a linear regression using raw species richness and longitude values from all Pitcairn and Tuamotu samples, and this indicated that increasing longitude (east to west) had a strongly significant positive effect on species richness ($t = 8.78$, $p < 0.0001$) (Figure 4.16, Figure 4.17, Figure 4.18).

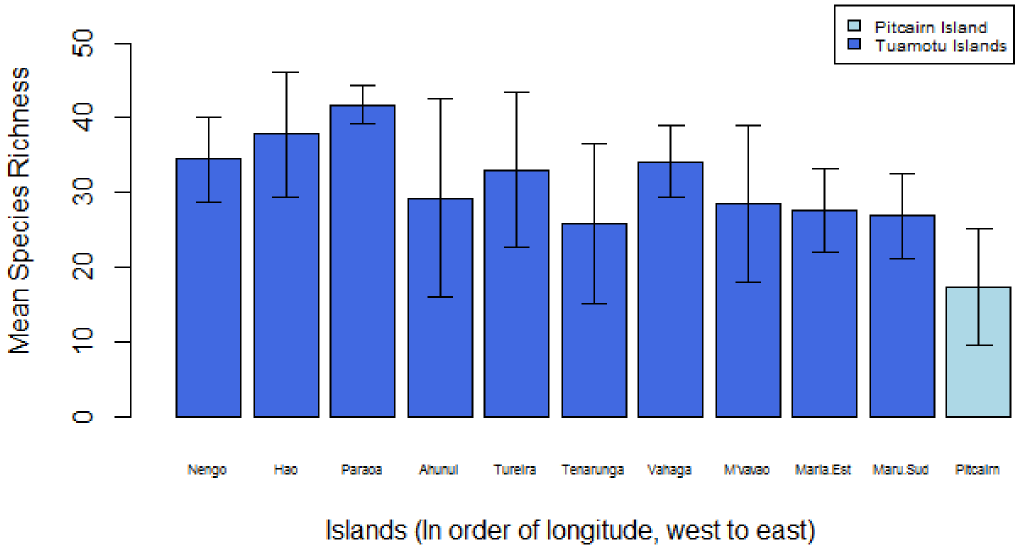

Figure 4.17 Mean species richness per sample from Pitcairn and ten atolls in the Tuamotu Islands, with values displayed across a longitudinal gradient.

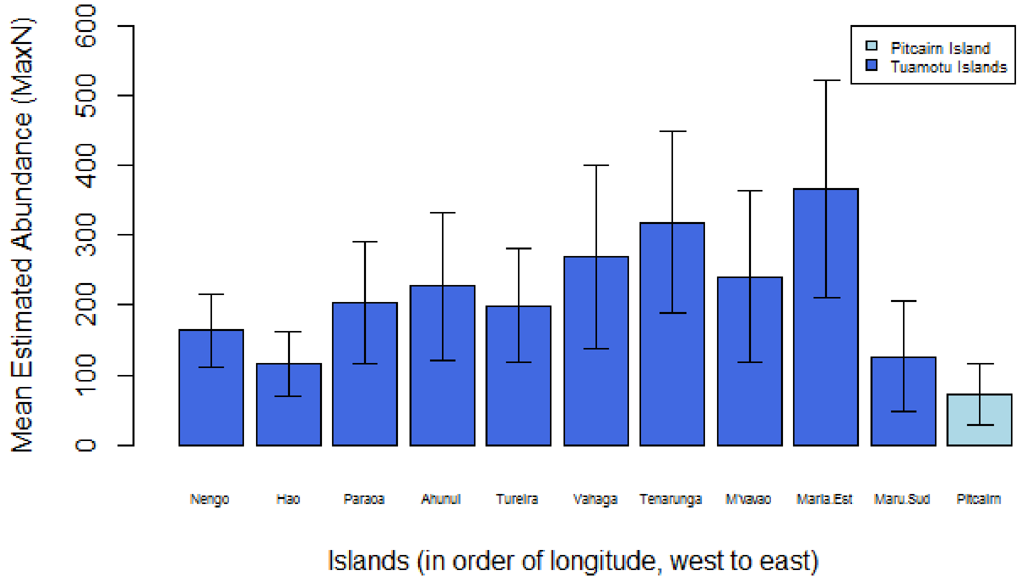

Figure 4.18 Mean estimated abundance per sample from Pitcairn and ten atolls in the Tuamotu Islands, with values displayed across a longitudinal gradient.

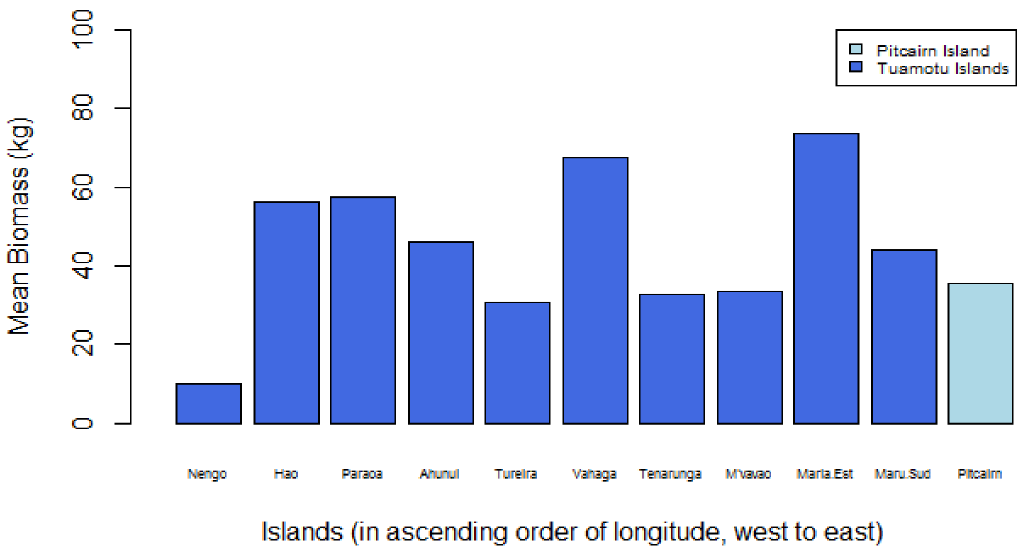

Figure 4.19 Mean top predator biomass per sample from Pitcairn and ten atolls in the Tuamotu Islands, with values displayed across a longitudinal gradient.

Initial t-tests were used to analyse the difference between mean values of inhabited and uninhabited islands (including Pitcairn). A significant difference was observed for abundance ($t = 2.51$, $df = 9$, $p < 0.03$), but significant results were not obtained for top predator biomass ($p = 0.056$) or species richness ($p > 0.9$).

Pitcairn's mean values were then separated, plotted and compared to means from inhabited and uninhabited Tuamotu islands (Figure 4.19, Figure 4.20, Figure 4.21). An ANOVA of species richness found no significant variance between habited and uninhabited islands in the Tuamotus ($p > 0.06$) but found species richness on Pitcairn to be significantly lower than both ($p < 0.0002$). Kruskal-Wallis tests also found that abundance ($p < 0.0004$) and top predator biomass ($p < 0.02$) varied significantly between Pitcairn and the groups of inhabited and uninhabited Tuamotu islands

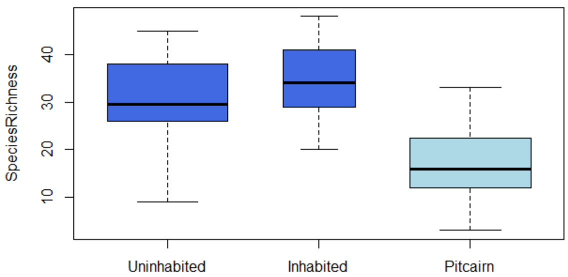

Figure 4.20 Comparison of Pitcairn's mean species richness per sample with inhabited and uninhabited islands in the Tuamotus

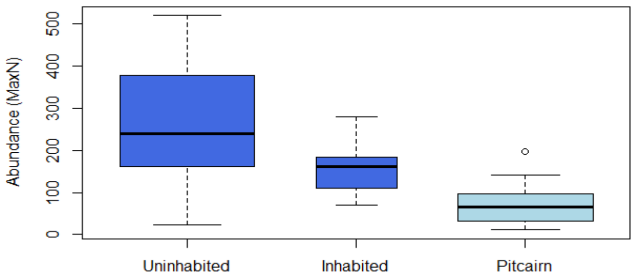

Figure 4.21 Comparison of Pitcairn's mean abundance per sample with inhabited and uninhabited islands in the Tuamotus

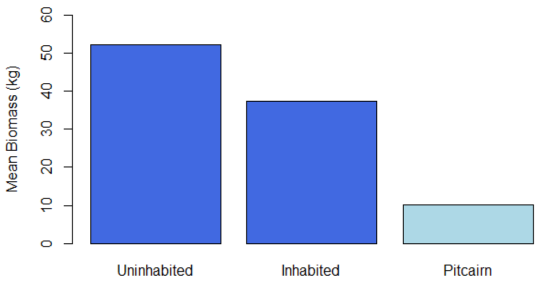

Figure 4.22 Comparison of Pitcairn's mean top predator biomass per sample with inhabited and uninhabited islands in the Tuamotus.

4.9.3 Measurement Comparisons

Sufficient measurements were obtained in both sampling programmes to allow mean computed lengths of blacktip grouper, yellow-edged-lyretail and black trevally to be compared (Figure 4.20).

A t-test (with equal variance) of yellow-edged lyretail lengths indicated a significant difference ($p < 0.02$), and a Welch t-test of black trevally lengths also returned a significant result ($p < 0.01$). A further Welch t-test of blacktip grouper lengths did not indicate a significant difference ($p = 0.58$).

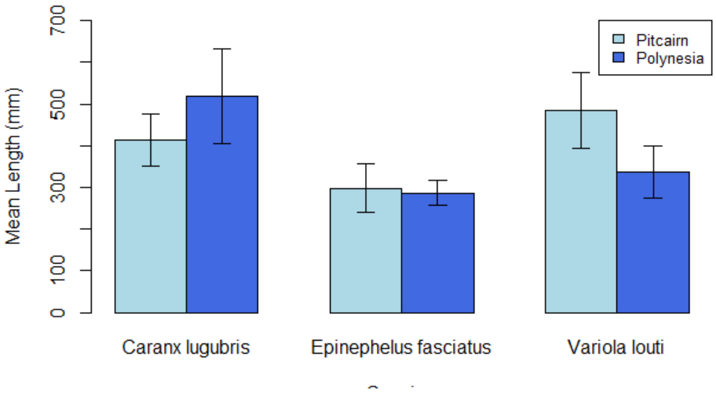

Figure 4.23 Comparison of mean computed lengths from Pitcairn and the Tuamotus for black trevally (*C.lugubris*), blacktip grouper (*E.fasciatus*) and yellow-edged lyretail (*Variola louti*).

Chapter 5: Discussion

Quantitative BRUV data analysis has allowed the structure of the Pitcairn fish assemblage to be assessed across multiple metrics. This chapter will discuss the significance of this study for future BRUV research and place Pitcairn's fish assemblage in both local and global contexts. The implications of this study for future fisheries management and conservation policy on Pitcairn will also be considered. Finally this section will evaluate to what extent the aims and objectives of the thesis have been achieved.

5.1 Sampling Programme Review

BRUV sampling achieved broad spatial coverage, with deployments guided by National Geographic's eleven SCUBA sites (Sala *et al.,* 2012) in addition to designating previously un-sampled sites. Extrapolated species richness values, which averaged at 115.57 (±16.16), suggest that sampling captured approximately 80% of total species richness (Appendix I). However, this also suggests that, whilst BRUV quantified the fish assemblage across a range of sites, insufficient samples were obtained to comprehensively assess the assemblage. Indeed fewer deployments were achieved than planned due to logistical issues and weather. Moreover repeat sampling was not undertaken, and inconsistent boat trips prevented consideration of temporal variations. Sampling effort in July was also biased towards the island's north (nearer the harbour) due to weather and the unavailability of the longboat, the only vessel capable of carrying frames to other sites. However, early longboat deployments had sampled the most exposed sites, maximising spatial coverage.

Sampling effort was evenly spread across the three depth categories, with at least ten deployments per category (for deployment sheet see Appendix II). However, the generally large p values and weak correlations observed in depth category analysis suggest that these divisions were not a helpful metric for discriminating variation. Correlation tests of raw depth values also suggested that depth was not a strong determining factor in species richness or abundance.

Sampling across habitat types was uneven, with 15 deployments in algae habitats compared to 5 in coral areas. Given the paucity of corals and abundant algae in Pitcairn's shallow waters (Sala *et al.,* 2012; Irving & Dawson, 2012), in addition to the methodology's prioritisation of depth and spatial coverage, some imbalance was likely. However, statistically significant results obtained from inter-habitat comparisons would suggest that coverage was sufficient to detect assemblage variation. Habitat was demonstrated to be a strong determining factor for species richness, overall abundance and top predator abundance, with substantial variation between the highest scoring habitat across all indices (coral) and the lowest (sand).

5.2 New Records & Range Extensions

This study identified three species not previously recorded by scientific surveys anywhere in the Pitcairn Islands, and two species known from elsewhere in the group but not Pitcairn itself.

Figure 5.1 BRUV image of *Xanthichthys caeruleolineatus* (Photo: H.Duffy.

- Blue-lined triggerfish *(Xanthichthys caeruleolineatus)*

Known from the Tuamotu Islands and Hawaii, but not previously recorded in the Pitcairn Islands (Allen *et al.*, 2007; Fishbase, 2014) (Figure 5.1)

- Black triggerfish *(Melichthys niger)*

Circumtropical and known to be distributed east to the Tuamotu Islands (Allen *et al.*, 2007; Fishbase, 2014), listed as a 'dubious' identification on Pitcairn but not recorded by scientific surveys (Ake-Gotesson, 2012).

Figure 5.2 BRUV image of *Seriola dumerili* (Photo: H.Duffy).

- Greater amberjack (*Seriola dumerili*)

Circumglobal and known from the Hawaiian Islands and New Caledonia but not previously recorded in the Pitcairn Islands (Fishbase, 2014, Irving, pers. comm., 2014). This individual was measured at 1.25m (Figure 5.2).

- Bridled parrotfish (*Scarus frenatus*)

Known from Ducie but not previously recorded on Pitcairn, Henderson or Oeno (Sala *et al.*, 2012; Irving, pers. comm., 2014).

- Giant trevally *(Caranx ignobilis)*

Known from Henderson, Oeno and Ducie, and caught near Pitcairn by offshore longlining, but not recorded in scientific surveys of coastal waters (Irving & Dawson, 2012). This individual was measured at 1.62m (Figure 5.3), and a second individual was also observed.

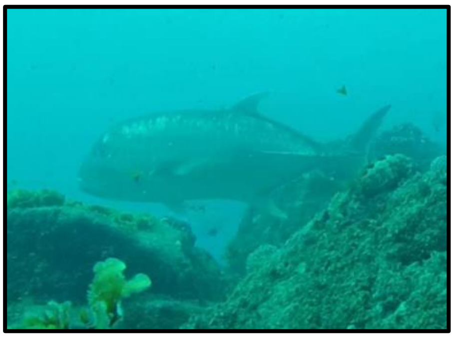

Figure 5.3 BRUV image of *Caranx ignobilis* (Photo: H.Duffy).

5.3 Implications for BRUV

On a fundamental level, this study has demonstrated the ability of BRUV to quantitatively assess a unique, scientifically valuable fish assemblage with minimal impact (Cappo *et al.*, 2006; Langlois *et al.*, 2010), obtaining measurement and biomass estimates which would otherwise require extractive sampling (Meekan *et al.*, 2006). Furthermore Pitcairn is unsuitable for a SCUBA survey programme, given the lack of recompression facilities and unreliable weather conditions, and BRUV provided a low risk, more flexible sampling approach (Koldewey, pers. comm., 2014). The measurement of 57 species and the acknowledged precision of EventMeasure as a measurement tool (Cappo *et al.*, 2006, Letessier *et al.*, in prep.), increased the accuracy with which the size ranges of species and assemblage biomass could be estimated, although the use of common lengths for 31 unmeasured species inevitably reduced biomass accuracy to some extent.

This research has emphasised other advantages of BRUV which are recognised in the literature. The ability of bait to attract large carnivores was evident (Meekan *et al.*, 2006; Watson *et al.*, 2010), with top predators estimated to account for 28.31% of assemblage biomass in comparison to 12% estimated by SCUBA surveys (Friedlander *et al.*, in prep.; Sala *et al.*, 2012). This attribute of BRUV is particularly valuable on Pitcairn given the historical prevalence of spearfishing (Ake-Gotesson, 2012), and the acknowledged diver avoidance behaviour exhibited by large carnivores at sites subject to spearfishing pressure (Lindfield *et al.*, 2014; Watson *et al.*, 2010). A mean of 4.17(±2.25 sd.) top predators per sample was recorded and two carnivores were observed on Pitcairn for the first time (see section 5.2). Bait also attracted cryptic carnivores which might otherwise remain concealed

(Watson *et al.,* 2010) with moray eels (Muraenidae*)* and hawkfishes (Cirrhitidae) recorded on 74.35% of samples. Three octopi (*Octopus* spp.) also consumed the bait, further demonstrating the power of BRUV to attract reclusive carnivores. However, an unexpected outcome was the sighting of only one shark (a grey reef) despite the bait incentive, whilst National Geographic recorded sharks on three of their 26 diver transects (Sala *et al.,* 2012). Although the diver surveys and the BRUV programme are not directly comparable, it was expected that baited cameras would sample a higher number of sharks.

The bait also attracted numerous non-carnivores, and the two most sampled species, gray drummer (*Kyphosus pacificus*) and crosshatch triggerfish (*Xanthichthys mento*), are herbivorous and planktivorous respectively. These species consumed the bait, as did several corallivorous butterflyfish species (*Chaetodontidae*), which demonstrated that many non-carnivores are not obligate feeders and will scavenge opportunistically (Watson *et al.,* 2010). Moreover gray drummer and crosshatch triggerfish fed more frequently than obligate carnivores such as groupers (*Serranidae*) and trevallies *(Carangidae*) which were observed on 89.74% of deployments but only fed on 25.12%. Other herbivores such as parrotfish (*Scaridae*) did not feed but regularly approached the frame, reflecting the acknowledged heterogeneity of fish behavioural responses (Watson *et al.,* 2005; Watson *et al.,* 2010).

This study also experienced limitations encountered by previous studies. Bait plume dispersal was not quantified, an almost impossible task in dynamic environments such as Pitcairn's shallow waters (Dorman *et al.,* 2012, Hardinge *et al.,* 2013). Instead this study used the recommended mitigation measures by maintaining 300m sample separation (Dorman *et al.,* 2012; Letessier *et al.,* 2013). Statistically significant differences between samples would suggest that the 'confounding' effect of unquantified dispersal did not prevent this study from detecting site specific variations, although the effect of bait dispersal remains unknown (Cappo *et al.,* 2003).

The reliance of BRUV sampling on underwater visibility has been previously highlighted (Cappo *et al.,* 2006; Watson *et al.,* 2010). Exceptional water clarity at deeper sites on Pitcairn provided ideal conditions for BRUV analysis, however high turbidity was experienced at several shallow sites, with substantial debris suspended in the water column. Consequently the power of certain samples was reduced, particularly when identifying individuals at a distance. However, the identification of 94.51% of individuals to species level indicates that poor visibility did not substantially handicap analysis. High turbidity also caused stability issues, exacerbated by the frames being lighter than previous models which used heavier equipment (Letessier, pers. comm., 2014). Occasionally swell caused frames to ‘rock’, which may have affected fish attraction, and on two occasions the frame was flipped over. The addition of weights is a possible solution, but this would increase the demands of hand-hauling. Indeed frame recovery was at times problematic during this study, with hauling occasionally hindered by snags or entanglement in rougher conditions. However, deep deployment hazards were reduced by two boats hauling in tandem using a pulley, a system which would lessen BRUV risks in the future.

A final point to acknowledge is that GoPro cameras may yield higher MaxN values than other cameras such as Sony HD models, owing to their wider field of view (Letessier, pers. comm., 2014). Thus the abundance estimates obtained for schooling species such as drummers and triggerfish, which on occasion filled the field of view, may have been affected by the choice of camera. However, the vast majority of MaxNs were obtained from around the bait, with species predominantly clustered in that central area (Letessier, pers. comm., 2014). Moreover this issue only arises when a schooling species fills the field of view, and most observed species on Pitcairn recorded low MaxN values per sample.

5.4 Biogeography

Comparison with the Tuamotus allowed the examination of biogeographical trends, with the results of plots and linear regression indicating decreasing species richness across a longitudinal gradient from west to east (see Section 4.9.2, Figures 4.17-19). This reflects the importance of the Indo-Pacific Coral Triangle as a ‘hotspot’ from which regional fish and coral biodiversity radiates (Allen, 2008), and the Triangle is also acknowledged to contain the most productive areas for zooplankton and phytoplankton in the Pacific (Carpenter, 1998; Longhurst 1998). Comparative analysis revealed significantly lower species richness on Pitcairn compared to the Tuamotus, and indeed the pool of 352 fish species in the entire Pitcairn group is substantially reduced in comparison to the 593 shore fish species alone recorded in the Society Islands, 1,500km to the west (Irving & Dawson, 2012). Therefore the results of this study’s comparative analysis reflect acknowledged biogeographical patterns. Pitcairn's distance from the Coral Triangle (Allen, 2008), and its location in an area of comparatively low productivity (Carpenter, 1998) are significant factors in determining the relatively low levels of fish diversity. However, it should be noted that the geographical isolation of the Pitcairn Islands has led to increased species endemism despite overall low richness (Allen, 2008; Sala *et al.*, 2012), and indeed BRUV sampling recorded four regionally endemic species including the abundant red and green coris (*Coris roseoviridis*) which recorded the third highest species MaxN (Appendix I).

5.5 Fish Assemblage Structure

Trophic pyramid analysis revealed that the fish assemblage is 'bottom heavy' in terms of biomass and abundance, with dominant herbivores and small carnivores. High algae coverage is probably key to the hyperabundance of gray drummer, the most numerous herbivore species (23.69% of total MaxN) which was recorded across all habitats and seen grazing on algae beds. Indeed recent research in Australia has observed a positive relationship between small herbivore abundance and increased algal cover on coral reefs (Ruppart *et al*., 2013). Drummers also consumed bait, suggesting dietary opportunism which may further explain their dominance over other herbivores such as surgeonfish (Acanthuridae) and parrotfish (Scaridae) which did not consume bait and accounted for just 5.99% and 1.66% of total MaxN respectively. Parrotfish are recognised as a 'functional group' within a fish assemblage, with higher parrotfish biomass associated with increased hard coral cover and reef resilience (Heenan & Williams, 2013), and thus the rarity of the family has potentially negative implications for the overall health of Pitcairn's shallow corals (Mumby *et al.*, 2013).

Small herbivores (pomacentridae) were also rare, accounting for 4.47% of total MaxN. In contrast pomacentrids in the Tuamotus accounted for 70.15% of total MaxN, a difference which might be attributed to higher coral cover as many pomacentrids are coral associated (Allen *et al.*, 2007). Indeed Vanderbilt's chromis (*Chromis vanderbilti*), the most common pomacentrid in Pitcairn samples, was only recorded at coral-dominated sites. Crosshatch triggerfish recorded the highest species MaxN and also displayed opportunistic scavenging behaviour, with the species schooling to consume bait despite being recognised as planktivorous (Sala *et al.*, 2012; Fishbase, 2014). Pitcairners have noticed similar behaviour, and the local name for the species is ‘Pick-Pick’ on account of their propensity to strip bait from hooks.

Despite abundant lower trophic level species, larger carnivores were rare. National Geographic’s diver surveys found that top predator biomass on Pitcairn was lower than the group’s other islands, with the trophic level accounting for 12% of assemblage biomass compared to 65% on Ducie (Friedlander *et al.*, in prep.). Whilst BRUV sampling recorded a higher percentage of top predator biomass on Pitcairn than the diver transects, the figure remains significantly lower than estimates for Ducie and Henderson (Friedlander *et al.*, in prep.) which were obtained without the use of bait. The paucity of Pitcairn’s top predators was emphasised by comparison with the Tuamotu Islands, where mean top predator biomass per BRUV sample was 48.04kghr compared to 10.14kghr on Pitcairn. Therefore the higher trophic levels of Pitcairn’s fish assemblage are noticeably reduced in comparison to both the other Pitcairn islands and assemblages in French Polynesia.

Furthermore the top predator biomass value obtained by this analysis might bias an assessment of assemblage structure, with 33.34% of the trophic level’s biomass accounted for by four individual fish; a giant trevally, greater amberjack, grey reef shark and unidentified tuna (*Thunnus* sp.). Thus the biomass value reflects the presence of large-bodied individuals rather than an abundance of top predators, as demonstrated by the fact that the trophic level only accounted for 5.88% of MaxN. Furthermore 28.65% of biomass was accounted for by predominantly pelagic species (*Seriola* spp. & *Thunnus* sp.) (Allen *et al.* 2007). These species may be attracted into shallow water by the bait but primarily live offshore and are not a permanent component of the reef-associated carnivore assemblage.

Indeed reef sharks and large reef-associated carnivores such as snapper and jobfish (Lutjanidae) were almost entirely absent from Pitcairn samples, whilst contrastingly abundant in the Tuamotus. A single grey reef shark, one jobfish (*Aphareus furca)*and nine blue-lined snapper (*Lutjanus kasmira*) were the only records from their respective families on Pitcairn. Red Snapper (*Lutjanus bohar*) was recorded on Pitcairn in the 1970s (Ake-Gotesson, 2012) but has not been recently observed (Irving & Dawson, 2012), although the species was recorded at Henderson, Ducie and Oeno in 2012 (Sala *et al.*, 2012). In addition Red Snapper are abundant in the Tuamotus, accounting for 20.21% of top predator biomass. The majority of sampled reef groupers (*Epinephelus* & *Cephalopholis* spp.) on Pitcairn were small, with yellow-edged lyretail (*Variola louti*) the only grouper measured above 400mm (Figure 5.4). This sole large species was rare, with only fourteen individuals sampled.

Figure 5.4 Yellow-edged lyretail caught in July 2014, with 15cm scale bar (Photo: H.Duffy).

5.6 Fisheries Implications

5.6.1 Historical Community Fishery

At present there has not been a functioning catch recording system on Pitcairn for several years, which limits the ability of this study to quantify the local artisanal fishery's ongoing scale and impact. However, until the 1990s catch data were recorded in the island's newsletter, the Pitcairn Miscellany, and the diving and fishing club also recorded catch into the late-2000s (Ake-Gotesson, 2012). These data enable some historical quantification of fishing pressure which may explain fish assemblage composition (Figure 5.4). Yearly catch data indicate variable but significant fishing pressure, with a mean of 8033.85 fish (±2269.85) caught annually between 1976 and 1996 (Figure 5.5) (Ake-Gotesson, 2012). Whilst species-specific numbers or size data are not available, the quantities of catch may explain the rarity of large carnivorous species such as groupers and trevallies which are targeted by fishers (Ake-Gotesson, 2012, Christian, B., pers. comm., 2014) The historical prevalence of spearfishing on Pitcairn may also explain the low density of parrotfish, which are acknowledged as vulnerable to spearfishing pressure (Lindfield, *et al.*, 2014) and specifically targeted by islanders with this method (Brown, pers.comm.,2014).

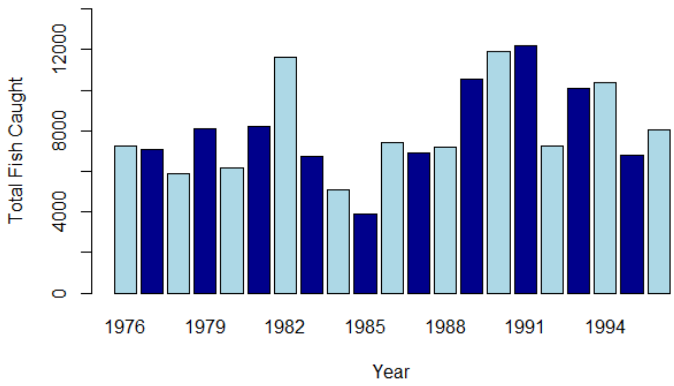

Figure 5.5 Annual catch figures for all fish species between 1976 and 1996, as recorded in the Pitcairn Miscellany (Ake-Gotesson, 2012).

The annual data do not contain shark catch records, but monthly statistics briefly collected between 2006-2008 state that 28 sharks were caught over 20 months (Ake-Gotesson, 2012). A long term shark fishery exists on Pitcairn, with the animals targeted by overnight baited lines (Ake-Gotesson, 2012; Brown, pers. comm., 2014). The teeth are extracted for use in souvenir carvings, but fins and meat are usually unused (Figure 5.6) (Sala *et al.,* 2012). This historical targeting might explain the rarity of the taxa on Pitcairn, in contrast to high shark biomass at Henderson and Ducie which are uninhabited and acknowledged to suffer from little or no fishing impact (Friedlander *et al.,* in prep.). Moreover sharks were also abundant at unfished 'pristine' atolls in the Tuamotus, with grey reefs alone accounting for 26.05% of top predator biomass.

Figure 5.6 Detail of a Pitcairn carving, with extracted shark teeth set in the jaw (Photo: H. Duffy).

This reflects acknowledged global trends which show top predator abundance to be substantially higher at uninhabited, remote 'marine wilderness' sites such as the Chagos marine reserve, in comparison to both fished sites and no take areas (NTAs) in locations of high anthropogenic impact (Graham & McClanahan, 2013). The structure of Pitcairn's assemblage is reflected in global data on the reef fish communities of anthropogenically impacted islands (Graham & McClanahan, 2013), with biomass dominated by low trophic level species Therefore, although Pitcairn's historical artisanal fishery is small-scale, evidence suggests that top predators have been over-exploited, thus creating the 'bottom heavy' assemblage recorded by BRUV. Sharks and other large carnivores such as grouper are acknowledged to be especially ecologically vulnerable to overfishing (Worm *et al.,* 2013; Morris *et al.,* 1999), and this may have contributed to the depletion of these taxa on Pitcairn despite fishing pressure being comparatively low by global standards (Worm *et al,* 2013; Koldewey, pers. comm., 2014).

Recent population decline (roughly halved in the last half century) in addition to Pitcairn's ageing demographic is likely to have reduced fishing pressure (Schuttenberg & Dawson, 2012). Monthly catch data from the mid-2000s support this inference, with 3930 fish caught in 2008 which suggests a decrease compared to mean catch 1976-1996. A decline has almost certainly continued up to 2014, with fishing trips observed rarely during 3 months of field work on Pitcairn and a recent questionnaire indicating reduced fishing activity across households (Schuttenberg & Dawson, 2012). Furthermore stricter hygiene laws have reduced the number of ships willing to purchase fish, a historical cause of spikes in fishing activity (Ake-Gotesson, 2012). Steady fishing decline may have contributed to the hyperabundance of gray drummer, known on Pitcairn as 'Nanwe' despite the species being popular for subsistence (Appendix III) (Ake-Gotesson, 2012). Pitcairn fishers attest that drummer were historically only found at specific sites, but are now ubiquitous and easily caught (Figure 5.7) (Christian, S., pers. comm., 2014; Warren, pers. comm., 2014). As fishing has declined, drummer populations may have increased faster than large carnivorous species with longer life cycles, aided by the abundance of food algae (Ruppart *et al.,* 2013) and an absence of predators (Letessier, pers. comm., 2014). Crosshatch triggerfish hyperabundance may be explained by the 'mesopredator release' hypothesis whereby small carnivore abundance increases following extirpation of larger predators (Prugh *et al.*, 2009) and indeed this phenomenon is widely observed on coral reefs exposed to fishing pressure (Ruppart *et al.,* 2013). Furthermore crosshatches are not a subsistence fishing target (Christian, B, pers. comm., 2014), which may also contribute to their local dominance.

Figure 5.7 Gray drummers caught in July 2014 (Photo: H.Duffy).

In summary, the 'bottom heavy' assemblage sampled by BRUV on Pitcairn is markedly different from assemblages at 'pristine' unfished sites, both elsewhere in the island group (Sala *et al.,* 2012) and in the Indo-Pacific region (Graham & McClanahan, 2013). This is likely to be the product of a long term artisanal fishery targeting large reef predators, especially sharks. Recent fishing declines, driven by a population decrease, may have allowed small bodied herbivores and mesopredators to proliferate whilst reef-associated top predator populations appear not to have rebounded from historical depletion.

<u>5.6.2 Commercial Fishery</u>

The SPC has assessed the feasibility of creating a small-scale commercial fishery on Pitcairn for export to Mangareva in French Polynesia, with the aim of strengthening the island's economy (Blanc, 2011; Sharp, 2011). This section assesses the significance of BRUV data for three of the proposed fishery's target species.

- Gray drummer (*Kyphosus pacificus)*

The SPC identified drummers as Pitcairn's most abundant fish, and BRUV sampling also found the species to be dominant in numbers. This study's biomass analysis estimated a larger weight per individual (407g) than the SPC study (330g) which states that Pitcairn's drummer population could sustain the increased fishing effort required to meet commercial targets of at least 450kg per month (Sharp, 2011). The fact that drummers are attracted to bait in schools, as observed by BRUV and Pitcairn fishers, suggests that the species could be exclusively targeted (Warren, pers. comm., 2014). Abundance and size data from BRUV analysis indicate a healthy population of the species, but a quota system would be essential to ensure that this widespread fish isn't depleted by new commercial fishing pressure (Koldewey, pers. comm., 2014).

- Blacktip grouper (*Epinephelus fasciatus*) & yellow-edged lyretail (*Variola louti*)

The SPC recommended that these grouper species could not sustain an increase in fishing effort (Sharp, 2011). A comparison with computed measurements from the Tuamotus did not suggest that the species on Pitcairn were significantly smaller, and indeed both were more abundant on Pitcairn, but this study supports the SPC's conclusions due to the low density at which the species occurred (Sharp, 2011). Blacktip grouper were occasionally abundant in rocky habitats, with eight observed in one sample, but generally occurred at low density with a mean of 1.51 individuals per sample. Yellow-edged lyretail were rare, with only fourteen individuals recorded, and an increase in fishing pressure to meet commercial targets (Sharp, 2011) could extirpate the species from shallow waters, especially in light of the globally observed vulnerability of serranids to overfishing (Morris *et al.*, 1999).

The SPC's study concluded that the main barrier to a commercial fishery is lack of infrastructure, with a $30,000 cold supply chain needed to meet safety standards (Blanc, 2011). According to an update from Pitcairn's Director of Natural Resources in August 2014, the island is awaiting the completion of import permit applications from Mangareva, and export infrastructure is not developed (Christian, M., pers. comm., 2014). Therefore, whilst BRUV sampling has provided new evidence that can help inform the setting of catch levels, a commercial fishery is not currently logistically feasible (Sharp, 2011), and Pitcairn's decreasing manpower is a potential future obstacle to the venture.

5.7 Conclusions & Future Recommendations

By setting new quantitative information on Pitcairn's marine resources in biogeographical and anthropogenic contexts through comparison with regional and global data, this study has improved the understanding of Pitcairn's fish assemblage and highlighted evidence which may explain the observed assemblage structure. The value of BRUV as a precise, repeatable and environmentally sustainable method has been demonstrated, and the scientific foundation for future conservation and management decision-making on Pitcairn has been substantially expanded. This study has also made a contribution to the identified aims of the Darwin Project (Dawson *et al.*, 2013) by assessing habitats and key fisheries species. Moreover data have been obtained which mitigate some of the knowledge deficiencies identified by SPC (Sharp, 2011; Blanc, 2011). Finally, five species have been recorded on Pitcairn for the first time, reflecting the ongoing potential for new scientific findings in this remote, poorly studied ecosystem.

This study suggests that the sustainability of commercialisation is uncertain, particularly for grouper species, as a commercial fishery would represent a major increase in fishing pressure compared to the currently 'weak' levels (Schuttenberg & Dawson, 2012). Thus the application of BRUV data to setting catch levels and fishing quotas is recommended to inform management should the fishery be developed in the future. There is also potential for wider implementation of BRUV on Pitcairn, particularly on the globally unique deep coral reefs around the island which extend beyond 40m (Sala *et al.*, 2012). The use of mid-water BRUV systems (Letessier *et al.*, 2013; Santana-Garcon *et al.*, 2014) in offshore pelagic habitats around Pitcairn would also provide valuable data to inform the Darwin

Project's management plan, as the island fishery also targets offshore pelagic species such as yellowfin tuna (*Thunnus albacares*) and wahoo (*Acanthocybium solandri*) which cannot be effectively assessed by shallow, seabed-based BRUV sampling.

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Appendices

Appendix I: BRUV Fish Species List

* indicates a new record for Pitcairn Island, ** indicates a regional endemic, (x) indicates recorded outside the sampling hour and therefore excluded from analysis.

Family	Common Name	Scientific Name	MaxN
Acanthuridae	Whitespotted surgeonfish	*Acanthurus guttatus*	1
	Whitebar surgeonfish	*Acanthurus leucopareius*	34
	Striped bristletooth	*Ctenochaetus hawaiiensis*	3
	Bristletooth sp.	*Ctenochaetus* sp.	2
	Spotted unicornfish	*Naso brevirostris*	3
	Sleek unicornfish	*Naso hexacanthus*	2
	Orangespine unicornfish	*Naso lituratus*	7
	Unicornfish spp.	*Naso* spp.	14
	Bluespine unicornfish	*Naso unicornis*	98
Aulostomidae	Trumpetfish	*Aulostomus chinensis*	2
Balistidae	Moustache triggerfish	*Balistoides viridescens*	1
	Black triggerfish*	*Melichthys niger*	1
	Blue triggerfish	*Pseudobalistes fuscus*	11
	Halfmoon triggerfish	*Rhinecanthus lunula*	23
	Wedgetail triggerfish	*Rhinecanthus rectangulus*	11
	Scythe triggerfish	*Sufflamen bursa*	59
	Bridled triggerfish	*Sufflamen fraenatum*	8
	Blue-lined triggerfish*	*Xanthichthys caeruleolineatus*	1
	Crosshatch triggerfish	*Xanthichthys mento*	776
Bothidae	Peacock flounder	*Bothus mancus*	5
Carangidae	Island trevally	*Carangoides orthogrammus*	16
	Giant trevally*	*Caranx ignobilis*	1
	Black trevally	*Caranx lugubris*	10
	Bluefin trevally	*Caranx melampygus*	1
	Greater amberjack*	*Seriola dumerili*	1
	Yellowtail amberjack	*Seriola lalandi*	9
	Almaco jack	*Seriola rivoliana*	3
	Silver trevally	*Pseudocaranx dentex*	4
Carcharanidae	Grey reef shark	*Carcharhinus amblyrhyncos*	1
Chaetodontidae	Yellowback butterflyfish	*Chaetodon mertensii*	62
	Ornate butterflyfish	*Chaetodon ornatissimus*	3
	Dot & dash butterflyfish	*Chaetodon pelewensis*	30

	Fourspot butterflyfish	*Chaetodon quadrimaculatus*	7
	Reticulated butterflyfish	*Chaetodon reticulatus*	11
	Smith's butterflyfish**	*Chaetodon smithii*	18
	Longnose/big longnose butterflyfish	*Forcipiger* spp.	17
Cirrhitidae	Stocky hawkfish	*Cirrhitus pinnulatus*	1
	Arc-eye hawkfish	*Paracirrhites arcatus*	2
	Freckled hawkfish	*Paracirrhites forsteri*	1
	Halfspotted hawkfish	*Paracirrhites hemistictus*	3
	Hawkfish sp.	*Paracirrhites* sp.	2
Fistulariidae	Cornetfish	*Fistularia commersonii*	21
Holocentridae	Brick soldierfish	*Myripristis anaema*	2
	Big-scale soldierfish	*Myripristis berndti*	4
	Tahitian squirrelfish	*Sargocentron tiere*	1
Kyphosidae	Gray drummer	*Kyphosus pacificus*	656
Labridae	Blue-spotted wrasse	*Anampses caeruleopunctatus*	5
	Cigar wrasse	*Cheilio inermis*	4
	Clown coris	*Coris aygula*	22
	Red and green coris**	*Coris roseoviridis*	128
	Coris sp.	*Coris* sp.	2
	Barred thicklip wrasse	*Hemigymnus fasciatus*	2
	Celebes razorfish	*Iniistius celebes*	19
	Bluestreak cleaner wrasse	*Labroides dimidiatus*	9
	Rockmover wrasse	*Novaculichthys taeniourus*	1
	Ringtail wrasse	*Oxycheilinus unifasciatus*	7
	Fuentesi's wrasse(?)	*Pseudolabrus* sp.	2
	Red-shoulder wrasse	*Stethojulis bandanensis*	2
	Sunset wrasse	*Thalassoma lutescens*	103
Lethrinidae			
	Striped large-eye bream	*Gnathodentex aureolineatus*	10
Lutjanidae	Humpnose bigeye bream	*Monotaxis grandoculis*	2
	Smalltooth jobfish	*Aphareus furca*	1
Monacanthidae	Blue-lined snapper	*Lutjanus kasmira*	9
	Scribbled filefish	*Aluterus scriptus*	4
	Wirenet filefish	*Cantherhines pardalis*	3
Mullidae	Filefish sp.	*Cantherhines* sp.	3
	Goldsaddle goatfish	*Parupeneus cyclostomus*	13
	Island goatfish	*Parupeneus insularis*	26
	Many-striped goatfish	*Parupeneus multifasciatus*	53
	Sidespot goatfish	*Parupeneus*	20

		pleurostigma	
Muraenidae	Goatfish spp.	*Parupeneus* spp.	18
	Giant Moray	*Gymnothorax javanicus*	1
	Whitespotted moray	*Gymnothorax meleagris*	5
Ophichthidae	Moray spp.	*Gymnothorax* spp.	16
Pomacanthidae	Spotted snake eel(x)	*Myrichthys maculosa*	1
Pomacentridae	Angelfish spp.	*Centropyge* spp.	6
	Blackspot sergeant	*Abudefduf sordidus*	2
	Vanderbilt's chromis	*Chromis vanderbilti*	70
	Canary demoiselle**	*Chrysiptera galba*	31
Pempheridae	Tahitian damselfish**	*Pomachromis fuscidorsalis*	9
Scaridae	Copper sweeper	*Pempheris oualensis*	1
	Steephead parrotfish	*Chlorurus microrhinos*	1
	Parrotfish spp. (juv. steephead/daisy)	*Chlorurus* spp.	3
	Forsten's parrotfish	*Scarus forsteni*	8
	Bridled parrotfish*	*Scarus frenatus*	2
	Highfin parrotfish	*Scarus longipinnis*	18
Scombridae	Parrotfish sp.	*Scarus* sp.	4
	Dogtooth tuna	*Gymnosarda unicolor*	2
Serranidae	Tuna sp.	*Thunnus sp.*	1
	Flagtail grouper	*Cephalopholis urodeta*	13
	Blacktip grouper	*Epinephelus fasciatus*	59
	Hexagon grouper	*Epinephelus hexagonatus*	9
	Greasy grouper	*Epinephelus tauvina*	1
Siganidae	Yellow-edged lyretail	*Variola louti*	14
Zanclidae	Forktail rabbitfish	*Siganus argenteus*	7
	Moorish idol	*Zanclus cornutus*	5

Three octopi (*Octopus* spp.) and one green turtle (*Chelonia mydas*) were also recorded in the BRUV samples.

Appendix II: Pitcairn BRUV Deployment Summary Sheet

#	Site	Date	Code	Latitude	Longitude	Time In	Depth (m)	Habitat	Species Richness	Abundance (MaxN)
1	Off Down Isaac's	30/05/2014	3005Drop1	-25.06196	-130.09641	15:25	20	Drop Failed	N/A	N/A
2	The Crack	30/05/2014	3005Drop2	-25.06596	-130.09331	15:45	15	Coral	24	142
3	Off Tedside North	06/06/2014	0606Drop1	-25.0707	-130.0847	14:20	20	Algae	15	55
4	Off Tedside North	06/06/2014	0606Drop2	-25.062	-130.119	14:34	15	Algae	21	43
5	Off Tedside North	06/06/2014	0606Drop3	-25.058	-130.124	14:42	27	Algae	20	77
6	Off Tedside South	06/06/2014	0606Drop4	-25.066	-130.126	14:50	14	Drop Failed	N/A	N/A
7	Off Tedside South	06/06/2014	0606Drop5	-25.068	-130.128	14:56	21	Drop Failed	N/A	N/A
8	Timiti's Crack	10/06/2014	1006Drop1	-25.08166	-130.1066	11:38	10	Rock	27	112
9	Timiti's Crack	10/06/2014	1006Drop2	-25.08559	-130.10789	11:46	29	Coral	31	84
10	Gudgeon Harbour	10/06/2014	1006Drop3	-25.0751	-130.11453	11:57	17	Sand	14	93
11	Gudgeon Harbour	10/06/2014	1006Drop4	-25.07674	-130.11751	12:06	22	Sand	4	14
12	Gudgeon Harbour	10/06/2014	1006Drop5	-25.08095	-130.12117	12:13	30	Algae	6	20
13	Howland Point	11/06/2014	11061Drop1	-25.08148	-130.10103	10:47	19.5	Rock	31	93
14	Howland Point	11/06/2014	11061Drop2	-25.08654	-130.1008	10:57	30	Sand	6	130
15	Break Im Hip	11/06/2014	11061Drop3	-25.08008	-130.09731	11:09	9.5	Rock	12	33
16	Break Im Hip	11/06/2014	11061Drop4	-25.0813	-130.09433	11:17	21	Rock	22	94
17	Break Im Hip	11/06/2014	11061Drop5	-25.08522	-130.095	11:28	29	Algae	16	33
18	Nancy's Rock	11/06/2014	11062Drop1	-25.07784	-130.08841	12:45	20	Algae	16	66
19	Nancy's Rock	11/06/2014	11062Drop2	-25.0787	-130.084	12:53	30	Algae	23	45
20	Glenny Harbour	11/06/2014	11062Drop3	-25.0718	-130.08896	13:06	10	Coral	23	62
21	Glenny Harbour	11/06/2014	11062Drop4	-25.06979	-130.08904	13:12	20	Algae	14	49
22	Glenny Harbour	11/06/2014	11062Drop5	-25.06694	-130.08969	13:19	27	Rock	12	134
23	Flat Rocks	13/06/2014	13061Drop1	-25.05963	-130.10881	11:50	13	Sand	8	14

24	Flat Rocks	13/06/2014	13061Drop2	-25.05456	-130.10944	11:58	20	Rock	13	93
25	Down Nelly	13/06/2014	13061Drop3	-25.05156	-130.11067	12:05	33	Rock	13	58
26	Down Nelly	13/06/2014	13061Drop4	-25.06024	-130.11479	12:15	13	Rock	19	94
27	Down Nelly	13/06/2014	13061Drop5	-25.05288	-130.11296	12:25	20	Algae	15	76
28	John Mills Harbour	13/06/2014	13062Drop1	-25.06973	-130.12552	13:46	20	Sand	3	11
29	John Mills Harbour	13/06/2014	13062Drop2	-25.07069	-130.12869	13:56	30	Algae	20	94
30	Ginger Valley Stud	13/06/2014	13062Drop3	-25.07188	-130.12158	14:06	10	Rock	26	60
31	Ginger Valley Stud	13/06/2014	13062Drop4	-25.0743	-130.1219	14:15	20	Rock	9	52
32	Ginger Valley Stud	13/06/2014	13062Drop5	-25.07571	-130.12665	14:22	29	Rock	29	106
33	The Chair	10/07/2014	1007Drop1	-25.06328	-130.09732	13:00	11	Coral	29	125
34	The Crack	10/07/2014	1007Drop2	-25.06566	-130.09352	13:40	18.5	Coral	21	103
35	The Chair	15/07/2014	1507Drop1	-25.06125	-130.09521	13:45	24	Rock	17	198
36	St. Paul's Stone (in)	15/07/2014	1507Drop2	-25.06936	-130.09074	14:00	9.5	Algae	11	16
37	St Paul's Stone (out)	21/07/2014	21071Drop1	-25.06864	-130.08936	14:00	21	Rock	22	100
38	Bounty Bay	21/07/2014	21071Drop2	-25.06694	-130.09613	14:11	10.5	Algae	12	19
39	Off Down Isaac's	21/07/2014	21071Drop3	-25.06305	-130.09918	14:28	10	Algae	14	22
40	Off Matt's Rocks	21/07/2014	21071Drop4	-25.05649	-130.11003	14:43	15.5	Algae	14	26
41	Pool of Oo-ah-oo	21/07/2014	21072Drop1	-25.07261	-130.08769	15:45	14.5	Coral	33	107
42	Butt's Pool	21/07/2014	21072Drop2	-25.06862	-130.09344	15:59	7	Algae	9	12

Appendix III: Dictionary of 'Pitkern' Names for Common Fish Species on Pitcairn Island

Scientific Name	Common Name	Pitkern Name
Acanthocybium solandri	Wahoo	Kuta
Abudefduf sordidus	Blackspot sergeant	Mummy
Carangoides orthogrammus	Island trevally	Ofe
Caranx ignobilis	Giant trevally	Ulwa
Caranx lugubris	Black trevally	Ulwa
Caranx melampygus	Bluefin trevally	Ulwa
Chaetodon smithii	Smith's butterflyfish	Letas
Coris aygula	Clown coris	Miti
Coris roseoviridis	Red-and green coris	Elwyn's Trousers
Epinephelus fasciatus	Blacktip grouper	Red Snapper
Epinephelus hexagonatus	Hexagon grouper	Rock Cod/Cod
Epinephelus tauvina	Greasy grouper	Rock Cod/Cod
Kuhlia sandvicensis	Hawaiian flagtail	Whitefish
Kyphosus pacificus	Gray drummer	Nanwe
Mullidae (Parupeneus & Mulloidichthys spp.)	Goatfish (various species)	Beard-fish
Scaridae (Scarus & Chlorurus spp.)	Parrotfish (various species)	Uhu
Seriola lalandi	Yellowtail Amberjack	Kingie
Thalassoma purpureum	Surge wrasse	Puhu
Thalassoma lutescens	Sunset wrasse	Whistling Daughter
Thunnus albacares	Yellowfin tuna	Yellowtail
Xanthichthys mento	Crosshatch triggerfish	Pick-Pick
Variola louti	Yellow-edged lyretail	Fafaia