A comparison of two underwater visual sampling techniques used to estimate tropical reef fish communities

by

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To my family, for instilling in me a fascination and appreciation of the natural world.

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Abstract

Volunteer based monitoring programmes using underwater visual census (UVC) have been promoted and used as a cost-effective way to gather data on fish. It has been demonstrated that UVC methods can be subject to biases and errors. These errors and biases include estimation of the survey area, fish identification, density, and length. New developments in technology are resulting in increased use of diver-operated stereo video (stereo-DOV) surveys as a potential alternative to UVC. As stereo-DOV is being increasingly used for reef monitoring, it is important to understand how this method compares to standard reef monitoring methods such as UVC. The aim of the current study was to conduct UVC and stereo-DOV surveys at the same sites, and compare estimates of fish density, species richness, and fish length. UVC and stereo-DOV surveys were conducted in Honduras on coral reefs within the Cayos Cochinos Marine Protected Area (MPA), which allows only artisanal fishing, and Utila, which is open to all types of fishing. Generalized linear models (GLM) were used to test for an effect of survey method and protected area status on reef fish community structure. Compared to stereo-DOV, UVC produced significantly higher estimates of total fish density, species richness, mean fish length, and predatory and herbivorous fish densities. UVC estimated higher mean fish lengths in the MPA compared to the non-MPA (significant interaction between survey method and protection, $p<0.001$). This may be a result of bias caused by divers expecting larger fish in the MPA. The results of the current study indicate UVC and stereo-DOV methods differ significantly in their estimates of tropical reef fish community variables, and thus should not be used interchangeably. These results have implications for reef monitoring programmes and marine resource management.

List of Abbreviations

CCMPA: Cayos Cochinos Marine Protected Area

GLM: General Linear Model

HCRF: Honduran Coral Reef Foundation

MPA: Marine Protected Area

UVC: Underwater Visual Census

Stereo-DOV: Diver-operated stereo video

Stereo-BRUV: Baited remote underwater stereo video

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Introduction

Disturbance of the marine environment due to human activity is widespread and increasing in many parts of the world (Halpern et al., 2008, Worm & Branch, 2012). Marine Protected Areas (MPAs) have increasingly been used as a way to ameliorate these impacts, particularly in tropical reef environments (Agardy, 1997; Ward et al., 2001; Roberts & Hawkins, 2003; McClanahan et al., 2007). Reliable data on the effect of human disturbances on reef fish communities is important for marine management and conservation. It is also important for monitoring changes in the marine environment in response to environmental changes (Cheung et al., 2009). Gathering reliable data on reef fish assemblages is difficult, as all survey techniques are associated with some level of error and bias (Thompson & Mapstone, 1997; Edgar & Barrett, 2004). Many studies have compared a variety of non-destructive sampling methods on their accuracy and precision (Watson et al., 2010). Comparison studies on a variety of survey techniques have suggested no single method excels for all species (Watson et al., 2010), and that methodological biases have differing affects depending on the research question being asked (Stobart et al., 2007). For instance, some fish species are attracted to SCUBA divers conducting surveys. As a result, diver-based techniques tend to overestimate the abundance of these species (Watson et al., 2010). The opposite is true for fish species that avoid SCUBA divers. The challenge for monitoring programmes is to choose those survey techniques which most accurately and precisely address the ecological question of interest (Watson et al., 2010).

Underwater visual census (UVC), first used to assess fish densities and community structure of coral reef fishes in 1954 (Brock, 1954), has become a common method of gathering data on reef fish communities, particularly in areas requiring non-destructive sampling such as MPAs (Harvey et al., 2002; Shortis et al., 2009; Watson, 2005). While the UVC method is quick, easy-to-use, and inexpensive, it is often associated with errors and biases (Sale & Douglas, 1981; DeMartini & Roberts, 1982; Sanderson & Solonsky, 1986; Thresher & Gunn, 1986; Greene & Alevizon, 1989; St. John et al., 1990; Bortone et al., 1991; Mapstone & Ayling, 1993; Thompson & Mapstone, 1997; Harvey et al., 2001; Harvey et al., 2002; Harvey et al., 2004; Leopold et al., 2009). The sources of these errors and biases include:

- variability between observers (Darwall & Dulvy, 1996; Thompson & Mapstone, 1997);
- observer swimming speed (Mapstone & Fowler, 1988; Lincoln-Smith, 1988; St. John et al., 1990);
- the effect of SCUBA divers on fish behaviour (Chapman et al., 1974; Chapman, 1976; Chapman & Atkinson; 1986; Cole, 1994; Kulbicki, 1998; Francour et al., 1999);
- patterns of fish movement (Watson et al., 1995);
- the dimensions of the sampling area (Sale & Sharp, 1983; Fowler, 1987; McCormick & Choat, 1987; Mapstone & Fowler, 1988; Buckley & Hueckel, 1989; Ward-Paige et al., 2010);
- the method of counting fish (Sale & Douglas, 1981; DeMartini & Roberts, 1982; Kimmel, 1985; Bortone et al., 1986, 1991; Sanderson & Solonsky, 1986; Thresher & Gunn, 1986; Greene & Alevizon, 1989);

- the number of fish species being counted concurrently (Russell et al., 1978; Greene & Alevizon, 1989; Lincoln-Smith, 1989);
- magnification of objects underwater caused by the air-water interface (Harvey et al., 2001);
- impaired mental performance underwater (Baddeley, 1965; Baddeley et al., 1968. References from Harvey et al., 2001 and Harvey et al., 2002).

Errors and biases associated with UVC have been shown to affect the accuracy and precision of fish length estimates (Harvey et al., 2001; Edgar et al., 2004), estimates of survey area (Harvey et al., 2001), species richness (Brock, 1982), fish abundance and fish density (Thompson & Mapstone, 1997).

Diver-operated stereo video (stereo-DOV) has become increasingly used as a non-destructive method of surveying reef fish communities (Shortis et al., 2009). Several studies have indicated stereo-DOV outperforms UVC when used to estimate fish length and survey area (Harvey et al., 2001; Harvey et al., 2002; Harvey et al., 2004). As such, stereo-DOV may be a viable alternative or complement to traditional UVC techniques (Edgar et al., 2004). While several studies have compared UVC and stereo-DOV on certain aspects of fish assemblage, such as fish length (Harvey et al., 2001; Harvey et al., 2002; Harvey et al., 2004), few, if any, have compared their performance on a wide range of variables, such as fish density, species richness, and the density of predators and herbivores. Considering a variety of environmental variables simultaneously permits a better understanding of how the techniques compare in describing the fish assemblage structure as a whole (Watson et al., 2010). Surprisingly, despite their common use in protected areas, there is also a lack of data on whether UVC and video-derived estimates are affected by the level of protection of the area being surveyed (e.g. MPA versus non-MPA), and whether there is an effect of survey depth on stereo-DOV estimates. As stereo-DOV is being used in monitoring programs with increasing frequency, it is important to understand how it compares to UVC. The current study compared UVC and stereo-DOV techniques on estimates of total fish density, species richness, mean fish length, and predatory and herbivorous fish density in a protected (MPA) and unprotected study area. The effect of survey depth on stereo-DOV was also tested. The first null hypothesis tested was that UVC and stereo-DOV produce no difference in estimates of fish density, length and species richness, and that this holds both inside a marine protected area, and in a heavily fished area. The second null hypothesis tested was that estimates of fish density, length, and species richness did not differ at different survey depths was also tested.

Methods

Affiliated research organizations

The current study was conducted in collaboration with Operation Wallacea, an organization which partners with research institutions globally to conduct research programmes focused on conservation. Operation Wallacea has been conducting research on the Cayos Cochinos islands in collaboration with the Honduran Coral Reef Foundation (HCRF) since 2003, and Utila Island at the Coral View Research Station since 2006. The current study conducted research on the reefs within the Cayos Cochinos Marine Protected Area (CCMPA) and surrounding Utila, with the goal of contributing data to Operation Wallacea's ongoing research projects in these areas, as well as gathering data for an honours project. Operation Wallacea partners with The Reef Check Foundation, a non-profit organization that was founded in 1996 which uses volunteer SCUBA divers using UVC to help with the monitoring and conservation of tropical coral reefs worldwide. Operation Wallacea follows Reef Check protocols for its marine projects.

Survey period and locations

Underwater visual censuses (UVC) and stereo-video surveys (stereo-DOV) were conducted from late June to late August in 2011 around Utila Island and the Cayos Cochinos islands, which are approximately 52 km apart on the northern side of mainland Honduras (Fig. 1. a). Five dive sites were surveyed around Utila and within the Cayos Cochinos MPA (Fig. 1. b, c).

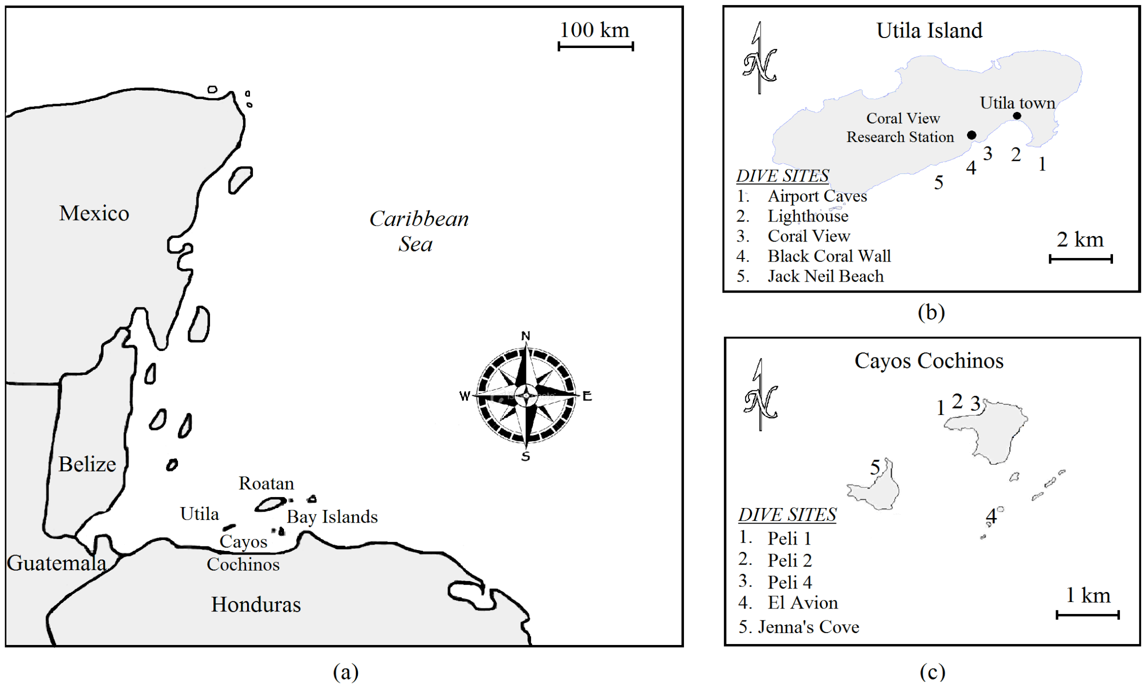


Fig. 1. Map of the study area, with survey sites. Utila island (b) and the Cayos Cochinos islands (c) are located in the Caribbean Sea on the northern side of Honduras between the mainland and the Bay Islands (a).

UVC and stereo-DOV surveys were conducted at each of the 10 dive sites over the duration of the study. During the 10-week period, 5 weeks were spent surveying in Utila, and 5 in Cayos Cochinos. Though efforts were made to conduct UVC and stereo-DOV surveys during the same dive (more or less simultaneously), due to logistical constraints, such as the availability of boats and trained stereo-DOV operators, some of the surveys were conducted a few hours to a few days apart. Surveys were conducted during daylight hours between 7:00 and 16:00. The visibility was generally fair, with the exception of 2 dives which had poor visibility.

Study areas

Utila is an island northwest of the Cayos Cochinos, off the coast of Honduras (Fig. 1a). It has a large permanent population, and is a popular destination for dive tourism due to its surrounding coral reefs. Mangroves, wetlands, and lagoons make up about 70% of the total island. In the last 15-20 years, Utila has developed rapidly, with the construction of numerous hotels, restaurants, and bars to support its tourism industry. Utila's tourism industry accounts for 90% of its economy, the remaining portion coming mostly from fishing-related industries. Data on fishing intensity and targeted species is sparse, but anecdotal accounts suggest fishing is having a severe impact on reef fish populations, particularly predatory species, which are the preferred catch in adjacent areas (Honduras Marine Science Report, 2008).

The Cayos Cochinos are a small group of islands located in the Caribbean Sea on the northern side of Honduras between the mainland and the Bay Islands (Fig. 1a). The islands include Cochino Pequeno, Cochino Grande, and 13 smaller sand cayes, including Chachahuate, which has a resident population. Cochino Pequeno is about 1.3 km long and 1 km wide, while Cochino Grande is 1.7 km long and 1.8 km wide. The associated reefs are a continuation of the Mesoamerican reef system which extends southward from the Yucatan Peninsula, Mexico, comprising the 2nd largest barrier reef system in the world. Due to the high biological diversity of the islands and surrounding area, Cayos Cochinos was established as a Marine Protected Area in 1993 and is considered a national monument. Prior to protection, Cayos Cochinos experienced intense fishing pressure from industrial, commercial, and artisanal fisheries which used a variety of fishing gears, including longlines and gillnets. Since its protection, fishing practices are restricted to hook-and-line fishing, and the area is monitored by the Honduran Navy and managed by the HCRF. The area of protection extends outward in all directions approximately 5 miles from the centre of the island, ending near La Ceiba in the west and Rio Esteban in the east (Fig. 2). The total area covered by the CCMPA is 460 km². The nearby communities of Nueva Armenia on the mainland and Chachahuate Island are permitted to fish in the CCMPA. A report by HCRF in 2008 identified the target species of these communities as *Lutjanus synagris*/lane snapper (50.8%), *Caranx crysos/*blue runner (12.7%), *Chirostoma estor/*whitefish (9.1%), *Micropogonias furnieri*/whitemouth croaker (4.0%), *Albula vulpes*/bonefish (3.1%), *Cephalopholis cruentata*/graysby (2.9%), *Scomberomorus regalis*/cero (2.8%), *Ocyurus chrysurus*/yellowtail snapper (1.3%), *Trachinotus goodei*/great pompano (1.3%), *Haemulon striatum*/striped grunt (1.2%) and *Haemulon macrostomum*/Spanish grunt (1.0%).

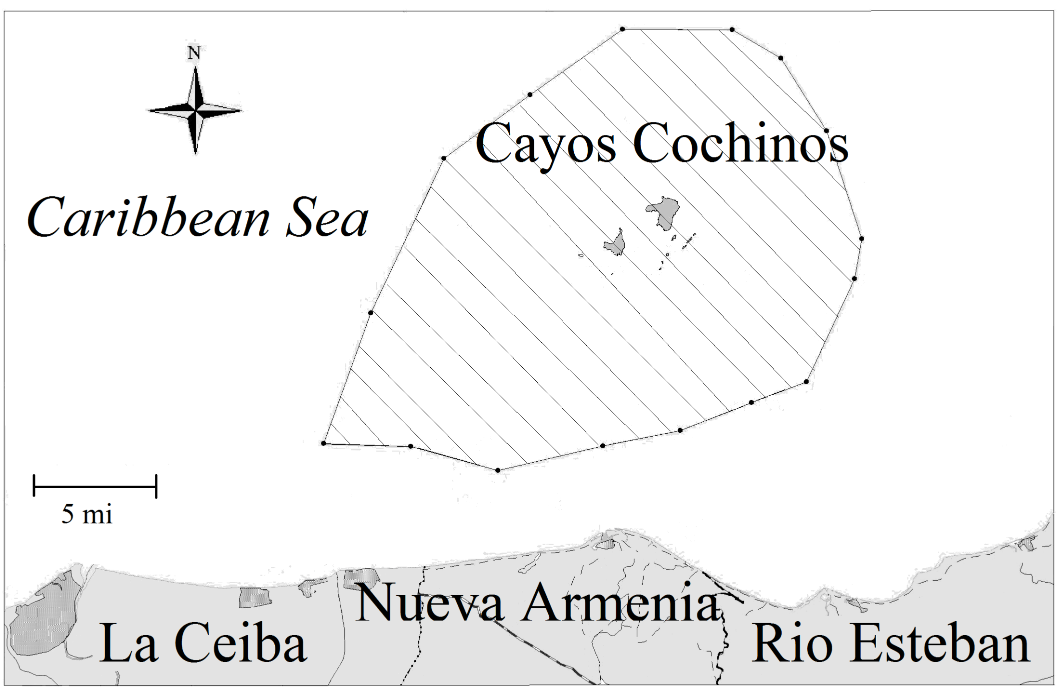


Fig. 2. Map of the Cayos Cochinos Marine Protected Area. Located at 15°58′76″ N, 86°28′67″ W, the area of protection extends approximately 5 nautical miles around the archipelago and covers 460 km².

Field sampling

Visual surveys were conducted using Underwater Visual Census (UVC). The methods described below are used throughout the Operation Wallacea sites as a standard protocol for long-term reef monitoring. The monitoring team consisted of Reef Check volunteers trained in Caribbean reef ecology a week prior to starting the surveys. Approximately 45 different volunteers conducted the Reef Check surveys over the 10-week duration of the study. Reef Check teams consisted of 5 divers, including a fish, invertebrate, and benthic observer, a diver to lay out the transect tape, and a Dive Master for safety purposes. Two survey replicates of 5x25 m belt-transects were laid at random points on the reef at depths of 8 and 12 m. Fish observers swam at a steady pace along the belt-transect, approximately 0.5 m above the substrate, taking about 10 minutes per transect, while counting fish in an imaginary 5x5x25 m box (Fig. 2).

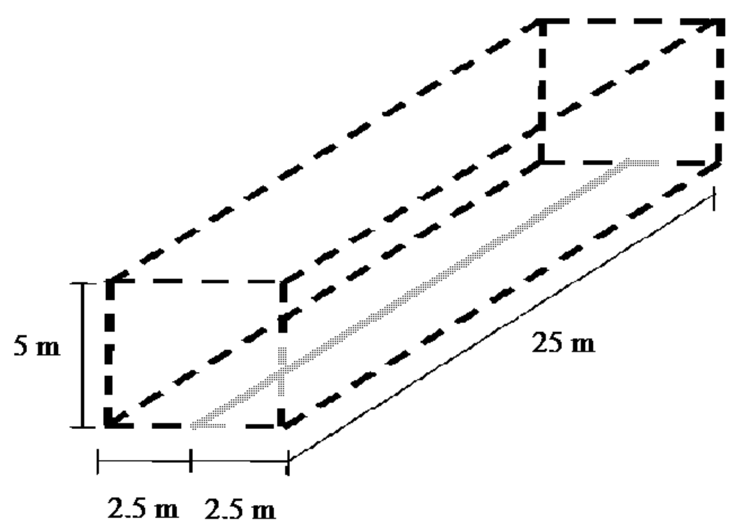


Fig. 3. Illustration of the method of estimating survey area dimensions used by Underwater Visual Census (UVC). Divers counted fish in an imaginary 5x5x25 m box along the belt-transect (grey line).

SCUBA divers conducting UVCs were instructed to swim along at a steady pace without stopping, so they generally did not deviate from the belt-transect to inspect crevices. UVC surveys in the current study were non-instantaneous, meaning fish that entered the survey area after the survey began were counted. This is the standard protocol used by Operation Wallacea. On a single dive, the total survey time for two 25 m transects was 15-20 minutes. Surveys included separate counts of Surgeonfishes (*Acanthuridae*), Jacks (*Carangidae*), Butterflyfishes (*Chaetodontidae*), Basslets (*Grammatidae*), Grunts (*Haemulidae*), Wrasses (*Labridae*), Goatfishes (*Mullidae*), Angelfishes (*Pomacanthidae*), Parrotfishes (*Scaridae*), Sea basses (*Serranidae*), Porgies (*Sparidae*), Barracudas (*Sphyraenidae*), and 5 other families from the orders *Tetraodontiformes* (Puffers), *Syngnathiformes* (Pipefishes), and *Beryciformes* (Alfonsinos). For a complete list of species included in the census, see Appendix A. The smallest fish included in the study were the fairy basslets (*Gramma loreto*), which were generally < 10 cm in length, and the largest was a stingray (*Dasyatis americana*). Fish observers estimated fish lengths of four fish families, Snappers (*Lutjanidae*), Groupers (*Serranidae)*, Grunts (*Haemulidae*) and Parrotfishes (*Scaridae*), using size intervals of 0-10 cm, 11-20 cm, 21-30 cm, 31-50 cm, 51-70 cm, 71-100 cm, and >100 cm.

The stereo-video surveys (stereo-DOV) followed the methods outlined in Watson et al. (2010). The system consists of 2 Canon HD cameras, model VIXIA HFS21, mounted 1 m apart on an aluminum bar in waterproof housings (Fig. 4). A diode, used to synchronize the video footage from left and right cameras, extends from the centre of the bar out in front of the cameras, which are angled slightly towards the diode (Fig. 4).

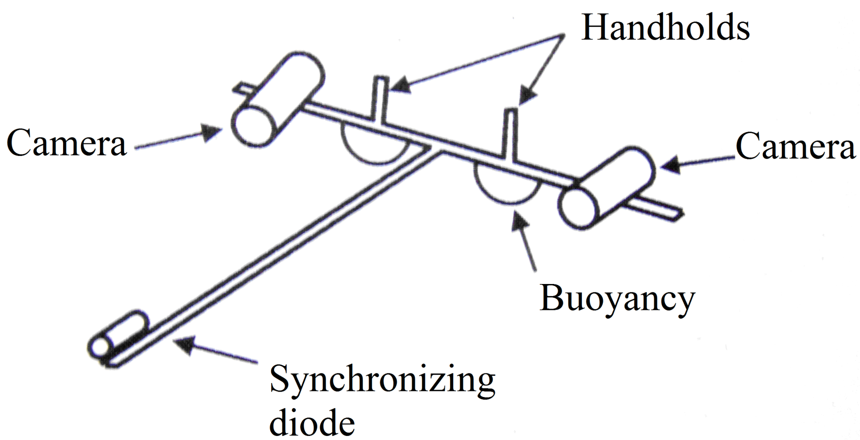


Fig. 4. Diagram of the stereo-video system (stereo-DOV). Two cameras in waterproof housings are secured on opposite ends of an aluminum bar. The cameras point toward a central diode which is used to synchronize left and right cameras during video analysis.

The 10 dive sites in Utila and Cayos Cochinos were surveyed at 8 and 12 m depths to match the UVC survey protocol. At each site, six 25 m transects were laid in a continuous line, separated by 10 m gaps. The stereo-DOV monitoring team consisted of 2 primary divers: a stereo-DOV operator and tape reel operator (to measure distance traveled). The stereo-DOV system operator and the tape reel operator started at the same position on the reef until the cameras were ready (Fig. 5). Once ready, the stereo-DOV operator would swim along the belt-transect at a fast and steady pace ahead of the tape reel operator with the cameras angled toward the reef. The tape reel operator would tug on the tape connected to the camera operator when the tape read 25 m. At this point, the stereo-DOV operator would stop swimming, and signal the end of the transect. Then both divers would swim 10 m before starting a new transect. After swimming 10 m, the stereo-DOV operator would stop, and wait for the tape reel operator to reel in the tape until they were positioned in the same spot once again. At this point a second transect survey would begin.

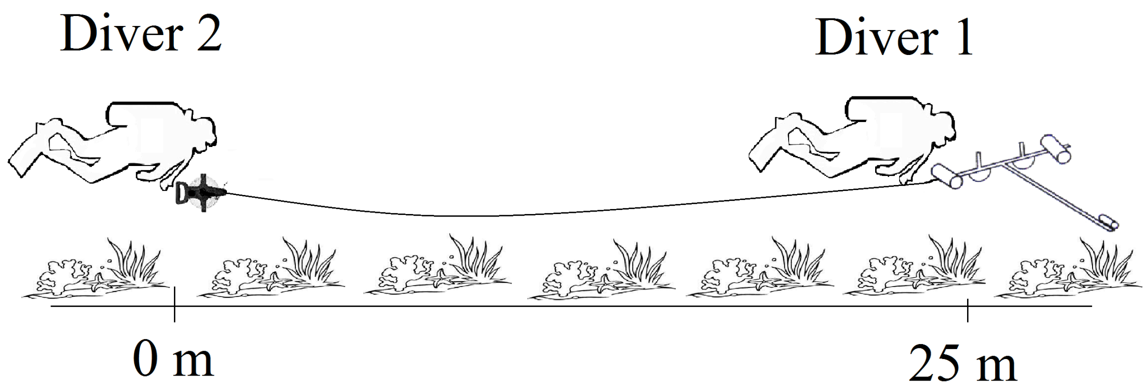


Fig. 5. Diagram of the stereo-DOV system sampling procedure. The tape reel operator (Diver 2) communicates with the camera operator (Diver 1) using the tape reel. Diver 2 remains at the start of the transect as Diver 1 swims ahead capturing video footage.

Prior to being used for surveys, the stereo-DOV system was calibrated using a large aluminum cube of previously measured dimensions (Fig. 6). Based on the rules of stereoscopy, stereo-DOV is then able to measure the dimensions of objects from 2D images.

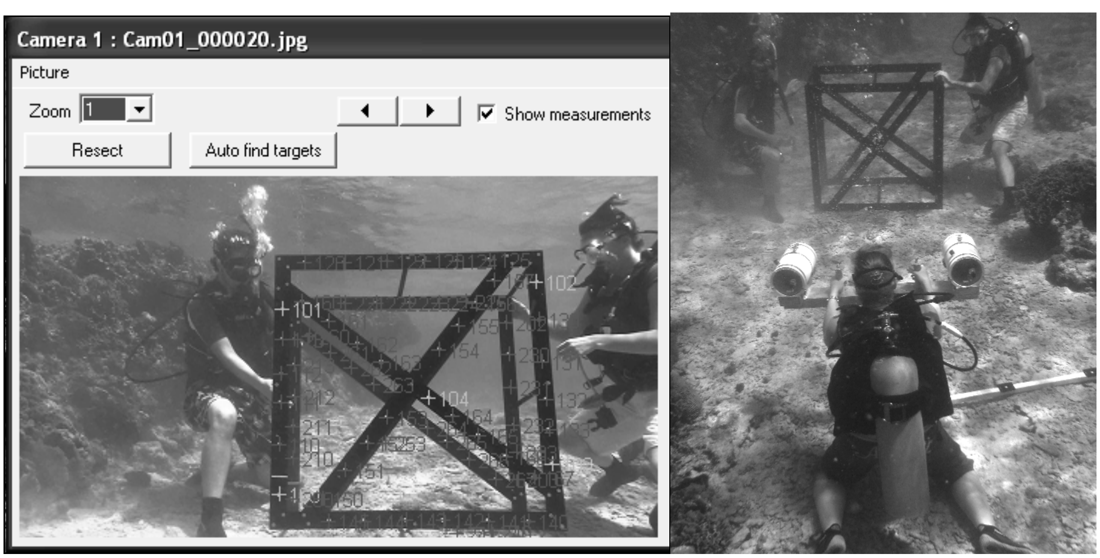


Fig. 6. Screenshot (left) and underwater photograph (right) of the calibration process. Stereo-DOV is calibrated using an aluminum cube of previously measured dimensions. Calibration provides an estimate of the length-estimation error of stereo-DOV, which is often less than 5 percent (Harvey et al., 2001).

A single dive during which six 25 m transects were surveyed took a total of 20-35 minutes (3.3-5.8 minutes/transect) to complete. The survey area was specified in the video analysis program to match the 5x5x25 m survey area used in the UVC surveys. The smallest species of fish identified by the stereo-DOV in this study were fairy basslets (*Gramma loreto*), and the largest was a stingray (*Dasyatis americana*).

Image analysis

Stereo-DOV footage was analyzed using EventMeasure, a computer program designed to analyze video gathered from stereo-DOV surveys. Footage from left and right cameras were synchronized in EventMeasure using the synchronizing diode. Individual fish were identified by family, genus, and species, and lengths were calculated from the snout to the base of the tail (Fig.7).

Fig. 7. Screenshot of a bluefin tuna being measured in the EventMeasure program for stereo-DOV video analysis from a previous study. (Photograph adapted from Shortis et al., 2009).

In EventMeasure, the video analyst is able to zoom in and out on individual fish, move forward and backward through frames to observe the fish at different angles relative to the camera, and use electronic reference material for fish identification.

Experimental design

Data on reef fish community structure was collected at two survey areas (Cayos Cochinos/MPA and Utila/fished area) using two survey methods (UVC and stereo-DOV). UVC surveys were repeated 6 times at each of the 5 dive sites in the MPA and 5 dive sites in the fished area. Stereo-DOV surveys were conducted 2 times at each of the same sites. The number of replicates differed between methods due to differences in survey duration. Stereo-DOV covers three times the number of transects covered by UVC in a single dive.

Statistical analysis

The abovementioned sampling programme provided UVC and stereo-DOV data on total fish density, species richness, mean fish length, and predatory and herbivorous fish density at the 10 dive sites (5 dive sites in the MPA, and 5 in Utila). Because stereo-DOV surveys took less time than UVC surveys, UVC surveys from multiple diving occasions were pooled to compare to data from stereo-DOV surveys.

Total fish density was calculated as the total number of individual fish counted per area surveyed (25 m transect length x 5 m transect width x 6 transects = 750 m^2). Species richness was measured as the total number of species identified per area surveyed (750 m^2 at each dive site). Mean fish length was measured differently between survey methods. For stereo-DOV surveys, mean fish length was measured using the

EventMeasure computer program. For UVC, mean fish length was visually estimated by observers based on size classes (binned size classes, described above), and the average length across all size classes was used for comparison with stereo-DOV estimates. The density of predatory fish was calculated as the sum of Groupers (*Serranidae*) and Jacks (*Carangidae*), while Parrotfishes (*Scaridae*) and Surgeonfishes (*Acanthuridae*) made up the herbivorous fish category. These particular groups were used as they represented the more abundant species groups in both survey areas.

Data on fish density, species richness, mean fish length, and predatory and herbivorous fish density were compared between 8 and 12 m survey depths (for stereo-DOV surveys only), survey techniques (stereo-DOV and UVC), and protected/unprotected survey areas (Cayos Cochinos and Utila, respectively) using generalized linear models (GLM) in the *Minitab 16* data analysis program. GLM's were used to test the main effect and interaction of survey depth, survey method, and site protection on each response variable (total fish density, species richness, mean fish length, and predatory and herbivorous fish density). A normal distribution was assumed, as residual plots approximated a normal distribution.

Although all surveys were conducted at a standardized depth (8-12 m) the exact sampling depth was not consistently recorded by Reef Check volunteers using UVC. Hence, the effect of sampling depth on fish community estimates could only be analysed from the stereo-DOV surveys, for which reliable depth data was gathered. The relationship between survey depth and reef fish community composition was thus included in a preliminary analysis to test whether data from surveys taken at 8 and 12m were significantly different, or could be pooled.

Results

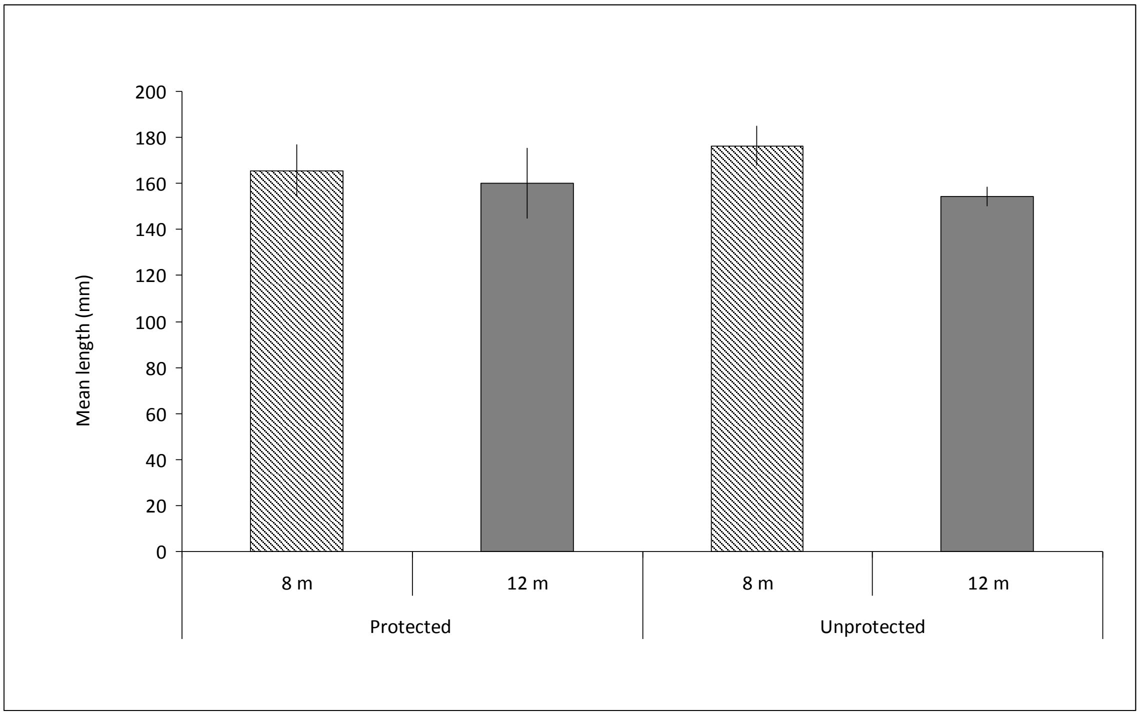
Effect of survey depth on estimates of reef fish community structure

GLM results comparing 8 and 12 m stereo-DOV surveys showed no significant effect of depth on estimates of fish density, species richness, mean fish length, or predatory or herbivorous fish density at either the protected (Cayos Cochinos) or unprotected (Utila) sites (Table 1 and Fig. 8). As no significant effect of survey depth on dependent variables was found, survey estimates derived at 8 and 12 m sampling depths were pooled for the subsequent analyses using UVC and stereo-DOV data.

Table 1. The effect of survey depth on estimates of reef fish community structure. Shown are p-values from the GLM. 'Site protection' refers to MPA/non-MPA status of Utila and Cayos Cochinos.

Survey estimate	Depth	Site protection	Depth x Protection
Fish density	0.888	0.532	0.827
Species richness	0.658	0.752	0.195
Mean fish length	0.213	0.812	0.449
Predatory fish density	0.500	0.821	0.334
Herbivorous fish density	0.967	0.065	0.555

***p<0.05 **p<0.01 ***p<0.001**



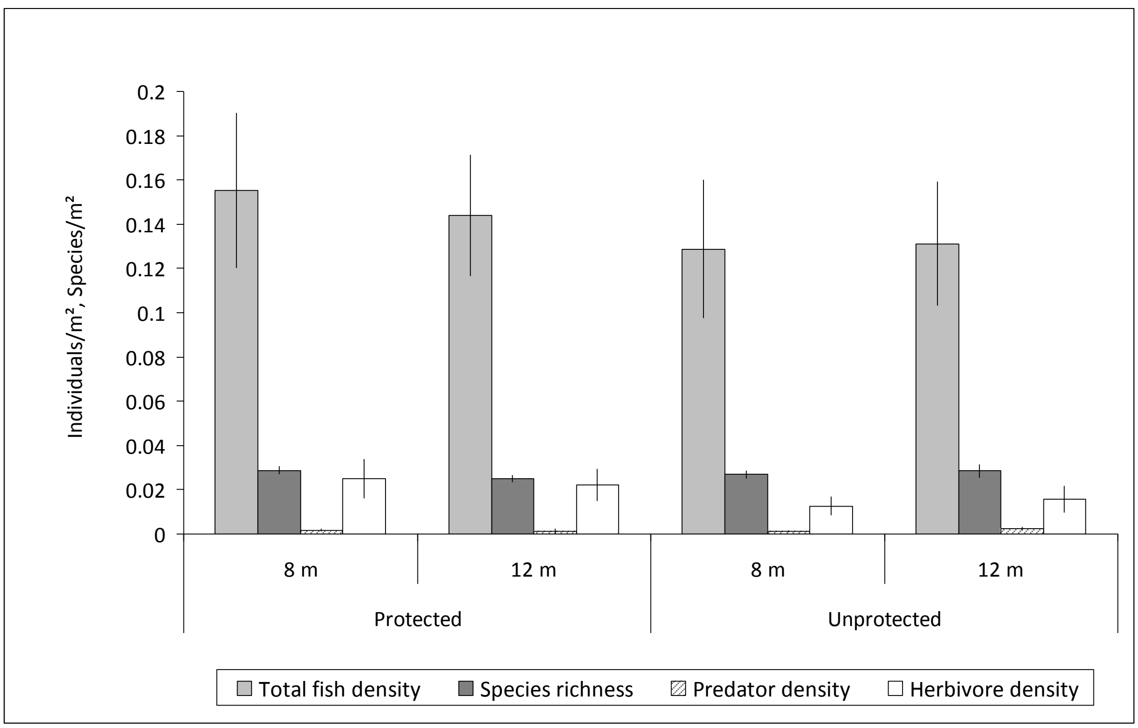


Fig. 8. Effect of depth on reef fish community variables in protected and unprotected areas. Depth was not found to have a significant effect on estimates of total fish density, species richness, predatory and herbivorous fish density (above), or mean fish length (below). Shown are mean densities and standard errors.

Effect of site protection and survey method on estimates of reef fish community structure

GLM results showed a significant effect of survey method (UVC versus stereo-DOV) on estimates of total fish density, species richness, mean fish length, and herbivorous and predatory fish densities. Site protection showed a significant effect on mean fish length and herbivorous fish density, which were both higher in the protected area. A significant interaction between site protection (MPA versus non-MPA) and survey method was found for estimates of mean fish length, as UVC estimated higher mean fish lengths in the protected area while SVS showed no difference in mean lengths between sites.

Table 2. The effect of site protection and survey method on estimates of reef fish community structure. Shown are p-values from the GLM. "Site protection" refers to MPA status of the survey areas.

Group variable	Site protection	Survey method	Method x Protection
Fish density	0.403	0.000***	0.220
Species richness	0.576	0.000***	0.836
Mean fish length	0.000***	0.015*	0.000***
Herbivore density	0.013*	0.001**	0.458
Predator density	0.314	0.002**	0.347

***p<0.05 **p<0.01 ***p<0.001**

Results from the GLM showed a significant effect of survey method on fish density ($p<0.001$, Table 2, Fig. 9). No significant effect was found for site protection on fish density ($p=0.403$). The interaction between site protection and survey method was also not significant ($p=0.220$).

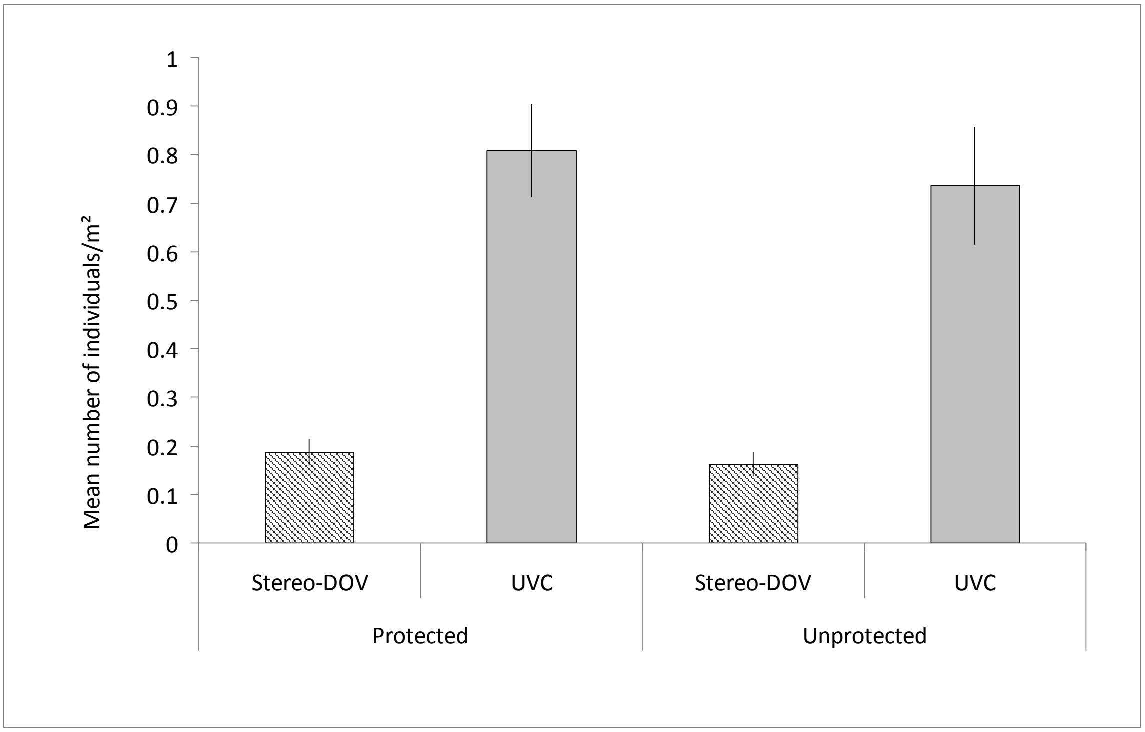


Fig. 9. Effect of survey method on fish density. GLM results showed fish density estimates were different between methods ($p<0.001$). Fish density was not different between sites.

Results from the GLM showed a significant effect of method on species richness ($p<0.001$, Table 2, Fig. 10). No significant effect was found for site protection on species richness ($p=0.576$). The interaction between site protection and method was also not significant ($p=0.836$).

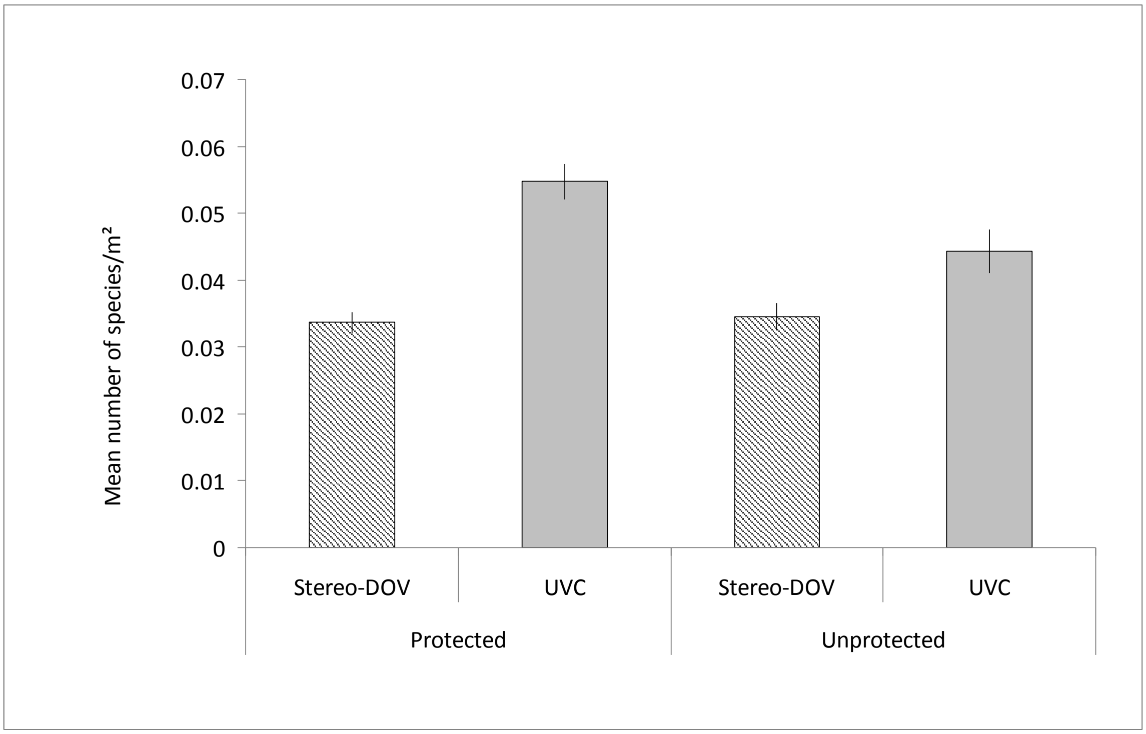


Fig. 10. Species richness estimates from stereo-DOV and visual surveys at protected and unprotected survey areas. GLM results showed species richness was significantly different between survey methods ($p<0.001$), but not between sites.

Results from the GLM showed a significant effect of method and protection on estimates of mean fish length (p=0.015 and p<0.001, respectively, Table 2, Fig. 11). A significant interaction was also found between method and protection on estimates of mean fish length (p<0.001).

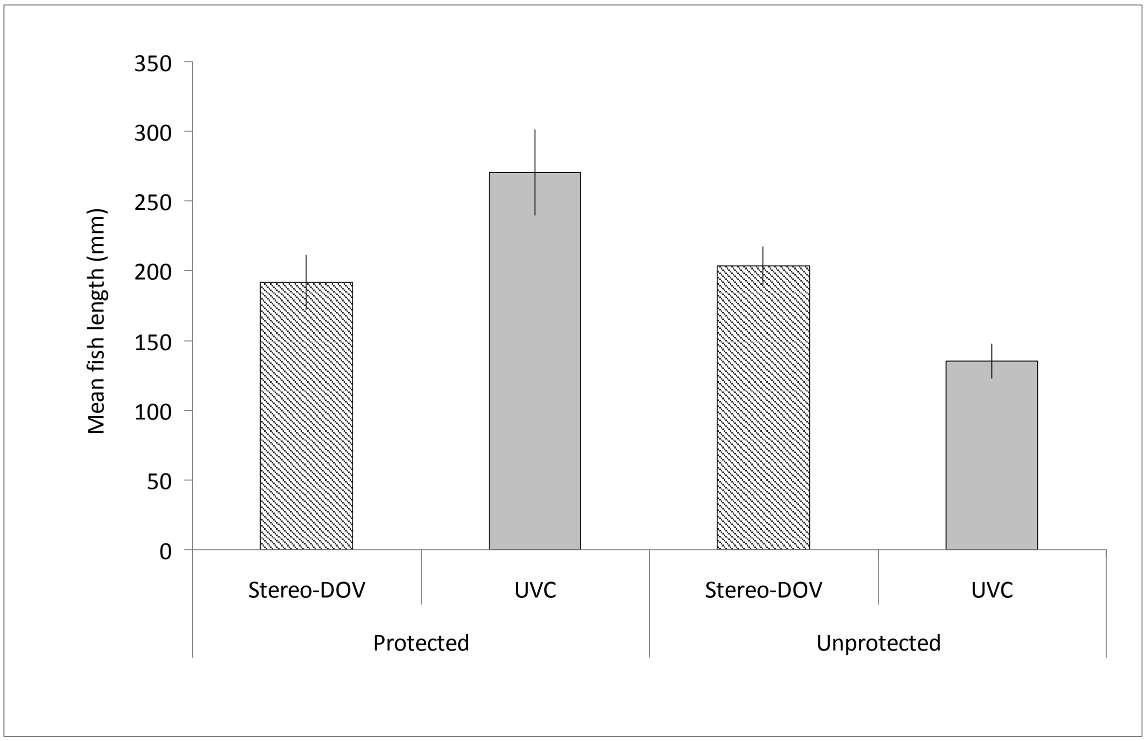


Fig. 11. Mean fish length estimates from stereo-DOV and visual surveys at protected and unprotected survey areas. GLM results showed a significant interaction between site protection and survey method for estimates of mean fish lengths produced by UVC divers (p<0.001).

Results from the GLM showed a significant effect of survey method on predatory fish density, indicating visual survey estimates of predatory fish counts were significantly higher than those estimated using stereo-DOV (p=0.002, Table 2, Fig. 12). No significant effect of protection was found on predatory fish density (p=0.314). The interaction between site and method was also not significant (p=0.347).

Survey method was found to have a significant effect on estimates of herbivorous fish density (p=0.001, Table 2). Counts of herbivorous fish by the visual survey method were significantly higher than stereo-DOV estimates (Fig. 12). A significant effect of site protection (p=0.013) was also found on estimates of herbivorous fish density, indicating overall higher estimates of herbivorous fish in the protected area compared to the unprotected area. The interaction between site and method was not significant (p=0.458).

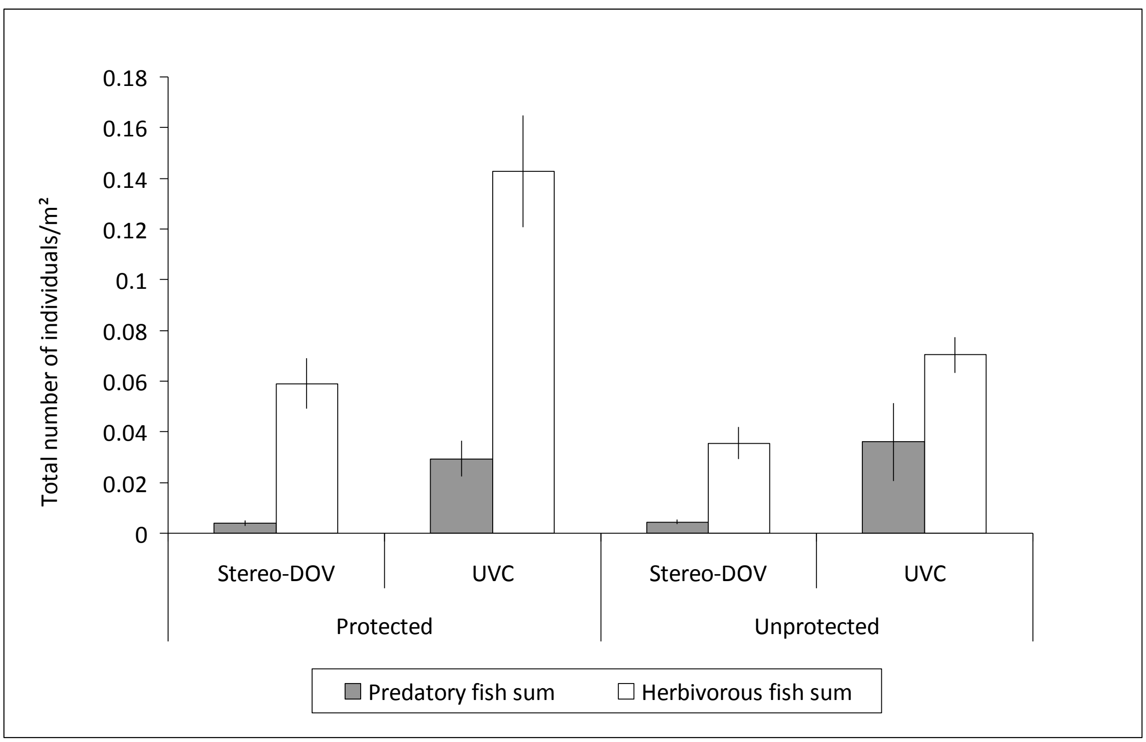


Fig. 12. Predatory and herbivorous fish density estimates from stereo-DOV and UVC in protected and unprotected areas. GLM results showed UVC produced significantly higher estimates of both predatory and herbivorous fish numbers than stereo-DOV (p<0.05). Both methods estimated more herbivorous than predatory fish at both sites, and more herbivores at protected sites.

Discussion

The primary aim of this study was to compare underwater visual censuses (UVCs) to diver-operated stereo-DOVs to test for an effect of survey method on fish density, species richness, mean fish length, and predatory and herbivorous fish densities. The secondary aim was to test for the effect of site protection on these metrics, and whether there was an interaction between site protection and survey method. An additional aim was to test for the effect of survey depth on stereo-DOV estimates. The results of this study found that:

1. UVC produced higher estimates of fish density, species richness, and mean fish length overall;
2. Site protection showed a positive effect on herbivorous fish density;
3. A positive effect of site protection on fish length was only found by UVC surveys, a possible indication of observer bias;
4. Survey depth did not have a significant effect on stereo-DOV estimates.

UVC produced significantly higher estimates of fish densities than stereo-DOV, at both protected and unprotected sites. Several possible explanations exist. First, visual observers have been shown to over-or-underestimate the actual dimensions of the survey area from 82-194%, resulting in a corresponding over-or-underestimation of fish density (Harvey, et al., 2004). This type of observer error may have contributed to the results of the current study. For example, if divers were overestimating the survey area and counting fish beyond the defined boundaries, they would be overestimating fish density, which may help account for the significantly higher fish density estimates (about 330% higher in the MPA and 350% higher in the fished area) shown by visual observers in this study, as compared to stereo-DOV estimates. In addition to error associated with estimating sampling area and consequently fish density, recent studies using simulation models have shown that fish speed, diver speed, visibility, survey area, and survey duration can significantly influence estimates of species abundance, biomass, and fish community structure, and that this effect is particularly evident for large, fast-swimming species such as sharks (Ward-Paige et al., 2010; McCauley et al., 2012). Ward-Paige et al. (2010) describes the problem of non-instantaneous surveys, wherein UVC divers count fish that enter the survey area after the survey begins, thereby overestimating the occurrence and abundance of mobile fish species. In the current study, UVC took twice as long as stereo-DOV, which, particularly for mobile fish species, may help account for the higher fish density estimates produced by UVC. An additional source of error associated with fish density estimates by UVC is the recounting of fish that enter the survey area more than once. Because stereo-DOV surveys were about 2 times faster than UVC, the likelihood of a fish re-entering the survey area would be reduced for stereo-DOV. UVC divers may be less likely to recount fish, having the advantage of peripheral vision, which stereo-DOV lacks. However, if stereo-DOV video analysts are more likely to recount fish due to the absence of peripheral vision, one would expect stereo-DOV results to overestimate fish density, which is not supported by the findings in this study.

The difference in estimates of fish density between methods may in part be due to how fish are counted by each method. UVC relies heavily on the diver's estimation of fish numbers, as fish speed, diver speed, schooling behaviour, and a number of other factors make it difficult to get an accurate estimate of the density of a mobile fish community. This is a problem inherent in any non-instantaneous survey (Ward-Paige et al., 2010). These factors may lead to inaccurate fish counts by SCUBA divers using UVC, and based on the findings of the present study, perhaps overestimation of fish density. Conversely, due to visibility constraints, stereo-DOV may underestimate fish densities. For instance, if the snout and tail of the fish are not visible in both the left and right camera frames (Fig.7.), or if the fish appears too small, too far from the camera, too blurry, or is obscured by features of the habitat, it will not be counted. In this manner, stereo-DOV surveys may underestimate fish density, particularly for species which exhibit hiding or schooling behaviour, or in high density areas with complex habitats. Although the results of this study found that UVC produced higher estimates of fish density than stereo-DOV, some studies have suggested UVC surveys may underestimate species richness due to the difficulty of surveying cryptic species (Brock, 1982), and fish density due to the inability to measure absolute abundance (Watson, 2005).

UVC was found to produce higher estimates of species richness than stereo-DOV at both protected and unprotected sites. Two possible explanations for this discrepancy involve differences in survey duration between methods (Pelletier, 2011) and in the ability of each method to detect certain species (Edgar, 2004). A recent study comparing UVC to stereo-DOV also found higher estimates of individual fish and species richness by UVC compared to stereo-DOV (Pelletier, 2011). The authors suggested the difference in species richness estimates between methods may in part be explained by the longer duration of UVC compared to stereo-DOV (45-60 minutes for UVC, and 4-10 minutes for stereo-DOV in their study). They argue that because visual surveys last longer, and divers spend more time underwater, divers are more likely to detect new species (Pelletier, 2011). This is the same non-instantaneous bias discussed earlier, in which the longer the survey duration and the faster the fish, the higher the probability of detection (Ward-Paige et al., 2010). In the present study, visual surveys lasted 7.5-10 minutes per transect on average, and video surveys lasted 3.3-5.8 minutes per transect (about half as long), so survey duration may have affected estimates of species richness.

A second possible explanation for differences in species richness estimates between methods has to do with the relative detectability of fish species by different methods (Edgar, 2004; Bozec et al., 2011). Numerous factors influence the detectability of fish, including fish size and behaviour, visibility, diver expertise, habitat complexity, and survey duration (Edgar et al., 2004; Pelletier et al., 2010; Ward-Paige et al., 2010; Bozec et al., 2011). The degree to which these factors influence fish detectability depends on how they interact with the particular method being used. Several studies have demonstrated that small cryptic fish are often underrepresented (Brock, 1982; Ackerman & Bellwood, 2000; Willis, 2001; and Edgar, 2004), and large, highly mobile fish are overrepresented by UVC compared to more accurate capture-resight and destructive sampling methods (Thresher & Gunn, 1986; Edgar, 2004).

Although not directly addressed in this study, other variations between the survey techniques such as number of divers, diver speed, and presence of survey equipment may have influenced fish behaviour. For example, in the current study, stereo-DOV usually required 2 divers while UVC involved 4-5 divers. Stereo-DOV divers swam faster and at a more constant pace than UVC divers, finishing six 25x5 m transects in about 3.3-5.8 minutes per transect, while UVC divers swam slower and with variable speed, covering the same area in about 7.5-10 minutes per transect. Whether the number of divers present in the survey area or the swimming speed of divers counting fish has a significant impact on reef fish survey estimates will need further examination.

UVC produced significantly higher mean fish length estimates of Snappers (*Lutjanidae*), Groupers (*Serranidae*), Grunts (*Haemulidae*) and Parrotfishes (*Scaridae*) in the protected area than the unprotected area, while stereo-DOV showed no significant difference in fish length between sites. One possible explanation to account for these results involves observer bias caused by divers' expectations. Previous studies have shown stereo-DOV produces more accurate and precise fish length estimates than UVC (Harvey et al., 2001; Harvey et al., 2002), which suggests the major differences in mean fish length between sites produced by UVC may reflect an aspect of UVC, such as magnification caused by the air-water interface or observer bias, rather than a defect of the stereo-DOV. A study by Leopold et al. (2009) found divers overestimate the abundance of target taxa in no-take zones when they are invested in the protection and success of the area, such as stakeholders or community members. It is possible that Reef Check volunteers conducting UVC in the MPA expected fish to be larger, on average, than those observed in the unprotected area, resulting in about a 66% overestimation of fish length in the protected but not the unprotected site. One shortcoming of the observer bias explanation is that along with larger fish, one would also expect UVC divers to anticipate more fish in the protected area, and yet the results of this study did not find UVC divers to estimate higher fish density in the protected area. These results suggests there may be factors apart from observer bias contributing to the higher estimates of mean fish length by UVC in the protected area. While the underlying reasons for this are outside the scope of this study, this will need to be examined in future studies. The results of the present study suggest observer bias based on divers' expectations of fish length in the protected area may help account for the disparity between UVC and stereo-DOV estimates, but may not be the only factor.

As with total fish density, UVC estimates of predatory and herbivorous fish density were significantly higher than those estimated by stereo-DOV. This finding is consistent with previous studies (Pelletier, 2011), and may in part be explained by non-instantaneous bias due to differences in survey duration (Ward-Paige et al., 2010). Both UVC and stereo-DOV showed no difference in predatory fish density between sites, but higher estimates of herbivorous fish densities at the protected site. This indicates a significant benefit of area protection for herbivorous, but not carnivorous fish. Several possible explanations for this exist. First, the discrepancy between the two species groups might be explained by the targeting behavior of local fishermen. While a broad range of species is targeted at the fully fished sites, a 2008 report on artisanal fishing in the CCMPA found most of the fish families targeted here were predators, including Snappers (*Lutjanidae*)*,* Jacks (*Carangidae*)*,* Grunts (*Haemulidae*)*,* and Groupers (*Serranidae*) (HCRF report, 2008). If fishers in the protected area are preferentially fishing predatory fish, this may help explain why predatory fish densities were found to be as low as they were in the fished area. Second, it is possible the area around Cayos Cochinos may be too small to effectively protect highly mobile predators such as jacks, grouper, barracuda, sharks, skates, and rays, which may migrate outside of the protected area. Third, previous studies have shown the presence of SCUBA divers (Chapman et al., 1974; Chapman, 1976; Chapman & Atkinson; 1986; Cole, 1994; Kulbicki, 1998; Francour et al., 1999) and baited sampling methods such as stereo baited remote underwater video (stereo-

BRUV) attract a higher diversity of species, and are better able to attract large-bodied and non-target species (Watson et al., 2010; Cappo & Brown 1996; Westera et al., 2003). Since both survey methods in the current study used SCUBA divers, and neither used bait, certain predatory species may have been missed.

Stereo-DOV surveys taken at 8 and 12 m depths did not differ significantly in fish density, species richness, mean fish length, predatory or herbivorous fish densities. While many studies have shown that reef fish assemblages vary with changes in habitat (Gladfelter and Gladfelter, 1978; Alevizon et al., 1985; Roberts and Ormond, 1987), it is possible that habitat variation between 8 and 12m was too minor to produce major changes in species composition or density. A study by Bouchon-Navarro (2005) on Caribbean reef fish found that even when fish assemblages were examined over a relatively large depth range (surface to 55m depth), depth was less influential on fish assemblages than other habitat variables such as latitude, hydrology, and habitat type. Another reason why depth may not have impacted survey estimates may have to do with the tendency of divers to unintentionally move up and down in the water column while swimming along a transect, often in response to schools of fish or other phenomena, thereby integrating over more than one depth horizon (personal observation).

Advantages and disadvantages of UVC and stereo-DOV methods

A list of the advantages and disadvantages of UVC and stereo-DOV surveys is presented in Table 3. One of the greatest advantages of stereo-DOV found in the present and previous studies is its ability to produce highly accurate fish length estimates (<5% error) with minimal influence of observer bias (Harvey et al., 2002; Watson, 2005). In comparison, underwater visual census produces less accurate estimates of fish length (30-40% error) and the present and previous studies have shown it can be influenced by observer bias, particularly when used in protected areas (present study) or when surveys are conducted by stakeholders (Leopold et al., 2009).

Among its disadvantages, stereo-DOV survey is less likely to record cryptic species, and therefore tends to underestimate species richness. For this reason, UVC, which allows divers to inspect holes and crevices, is probably a better tool to estimate species richness. In addition, stereo-DOV is likely to produce lower fish density estimates than UVC, due to its short survey duration (~3.3-5.8 minute/transect versus 7.5-10 minute/transect for UVC). Both UVC and stereo-DOV can only measure relative density (for stereo-DOV, number of fish in a single video frame), which likely underestimates true density (Watson, 2005).

Table 3. Comparison of the advantages, disadvantages, and sources of error of UVC and stereo-DOV survey methods. (Adapted from Watson, 2005).

Technique	Advantages	Disadvantages	Sources of error
Underwater Visual Census (UVC)	• Cost-effective • Easy to use • Quick data on abundance and diversity • Can detect cryptic species	• Inaccurate fish length estimates • Influenced by observer bias • Long survey duration • No permanent record • Multiple observers increases error	• Observer bias • Inter-diver variability • Air-water interface causes magnification of objects underwater • Reduced performance of SCUBA divers
Diver-operated stereo video (stereo-DOV)	• Precise and accurate fish length estimates • Less influenced by observer bias • Short survey duration • Provides permanent record	• High initial cost of equipment (~$5250CAN) • Time-consuming video analysis • Poor ability to record cryptic species • Underestimates fish density and species richness	• Visibility • Cameras unable to detect re-entrance of fish into survey area

Limitations of the study

There were a number of limitations in the current study. The individual dive sites surveyed in Utila and the CCMPA were assumed to be independent samples, despite their proximity (often dive sites were <1 km apart). In addition, Cayos Cochinos and Utila were used for the “MPA” and “non-MPA” comparisons, respectively. However, the sites may not be representative of typical protected and unprotected areas for several reasons. First, despite the protected status of Cayos Cochinos, certain types of fishing are still allowed on the island, and its proximity to the populated islands of Chachahuate, Cochino

Grande, and mainland Honduras likely affect its fish community. Second, although Utila is rapidly developing its tourist industry, and fishing is likely having an impact on its reef ecosystems, mangroves still make up approximately 70% of the island, which likely acts as a refuge and nursery for fish communities, bolstering the health of its reef systems. Utila is also further from the mainland than Cayos Cochinos, which may provide it with some refuge from pollution and other negative impacts.

The pervasiveness of SCUBA divers on the islands may have been another factor affecting results. Both Utila and the CCMPA were surveyed frequently, but the frequency of dives at each site was not accounted for in the results. The intensity of diving at the dive sites is likely to have impacted fish community variables such as fish density and species richness, so that if diving intensity varied between sites, this could have been a confounding variable in the results.

With regards to mean fish length, estimates were based on 4 fish families, Grunts (*Haemulidae*), Snappers (*Lutjanidae*), Parrotfishes (*Scaridae*), and Groupers (*Serranidae*), for which the results may have not have been representative of other fish families. In regards to predatory and herbivorous fish density estimates, each group (predators and herbivores) was comprised of two fish families, which may not have been representative of other predatory and herbivorous fish. Additionally, predatory fish density was low (on average, <5 individuals per 750m^2), and therefore the sample may not have been large enough to detect a significant effect of survey method or site protection.

Other limitations of the present study include variation in the number of divers between methods. While the same 2-4 divers conducted the stereo-DOV surveys, approximately 45 volunteers rotated for UVC surveys. The variation between UVC divers may have influenced the results and be represented in some of the unexplained variance. An additional limitation is that UVC and stereo-DOV were not conducted simultaneously. Because UVC surveys took longer to conduct, three UVC dives were pooled to compare to a single stereo-DOV dive. For this reason, temporal variations may have been a factor affecting the results.

In regards to survey depth, the pooling of data from surveys conducted at 8 and 12 m depths was based on the result that there was no effect of survey depth on stereo-DOV estimates, and the assumption that this would apply to UVC estimates as well. This is an assumption that needs to be tested in future studies.

Conclusions

The results of this study can be grouped into four primary findings: 1. UVC produced higher estimates of reef fish density, species richness, and mean fish length than stereo-DOV; 2. Site protection did not affect UVC and stereo-DOV estimates of total fish density, species richness, and predatory fish densities, but had a positive effect on herbivorous fish density; 3. Compared with stereo-DOV, UVC produced significantly higher estimates of mean fish length in the protected, but not in the unprotected survey area; and 4. Survey depth did not have an effect on stereo-DOV estimates of reef fish community variables. Until further studies identify the underlying causes of the differences between reef fish community estimates found in this study, caution is advised when comparing results from UVC and stereo-DOV techniques.

Implications and direction for future research

UVC, and increasingly stereo-DOV, are used by many scientific monitoring programmes to assess the status of reef fish communities and inform management and policy decisions. A significant implication of this study's findings is that UVC overestimates fish density and species richness relative to stereo-DOV, and is affected by the protection status of the survey areas in which it is used, particularly when used to estimate fish lengths. Reliable data on fish length is important for assessing the rate of growth, size composition, biomass, fishing intensity, rate of recovery from fishing, recruitment to the adult population, and human impacts on the ecosystem (Harvey et al., 2002). Thus, stereo-DOV may be a better choice than UVC when collecting data on fish length.

The current study sought to determine whether UVC and stereo-DOV techniques differed significantly in their estimates of reef fish community structure. Examination of the underlying reasons for these discrepancies, however, was beyond the scope of this study. Future research should confirm whether the results of the present study are repeatable, and, if so, whether observer bias, or additional factors, can account for the higher estimates of fish density, species richness, and mean fish length made by UVC divers. Understanding the causes of the differences between UVC and stereo-DOV estimates will provide information on the power of each technique to detect changes in the marine environment, and thereby help inform conservation programmes.

Appendix 1: Caribbean Species List

Family	**Genus**	**Species**
Acanthuridae	*Acanthurus*	*coeruleus*
	Acanthurus	*bahianus*
	Acanthurus	*chirurgus*
Aulostomidae	*Aulostomus*	*maculatus*
Balistidae	*Canthiderrmis*	*sufflamen*
Carangidae	*Caranx*	*ruber*
	Caranx	*latus*
Chaetodontida(	*Chaetodon*	*capistratus*
	Chaetodon	*striatus*
	Chaetodon	*ocellatus*
Grammatidae	*Gramma*	*loreto*
Haemulidae	*Haemulon*	*macrostomum*
	Haemulon	*flabolineatun*
	Haemulon	*sciurus*
	Haemulon	*plumierii*
	Anisotrenus	*surinamensis*
	Anisotrenus	*birginicus*
	Haemulon	*aurolineatum*
	Haemulon	*album*
	Haemulon	*carbonarium*
Holocentridae	*Holocentrus*	*rufus*
Kyphosidae	*Kyphosus*	*sectatrix*
Labridae	*Thalassoma*	*bifasciatum*
	Clepticus	*parrae*
	Halichoeres	*garnoti*
	Halichoeres	*maculipinna*
	Bodianus	*rufus*
	Halichoeres	*poeyi*
	Halichoeres	*radiatus*
Lutjanidae	*Ocyurus*	*chrysurus*
	Lutjanus	*apodus*
	Lutjanus	*analis*
	Lutjanus	*jocu*
	Lutjanus	*mahogoni*
	Lutjanus	*synagris*
	Lutjanus	*cyanopterus*
Mullidae	*Mulloidichthys*	*martinicus*
	Pseudupeneus	*maculatus*
Ostraciidae	*Acanthostracio*	*quadricornis*
Pomacanthidae	*Holacanthus*	*ciliaris*

	Pomacanthus	*paru*
	Pomacanthus	*arcuatus*
	Holacanthus	*tricolor*
	Stegastes	*adustus*
	Stegastes	*leucostictus*
	Stegastes	*partitus*
	Microspathodon	*chrysurus*
	Abiduefduf	*saxatilis*
	Chromis	*cyanea*
	Stegastes	*planifrons*
	Chromis	*multilineata*
	Stegastes	*diencaeus*
Scaridae	*Sparisoma*	*viride*
	Scarus	*vetula*
	Scarus	*coelestinus*
	Scarus	*coeruleus*
	Sparisoma	*chrysopterum*
	Scarus	*iserti*
	Scarus	*taeniopterus*
	Sparisoma	*aurofrenatum*
Scombridae	*Scomberomorus*	*regalis*
Serranidae	*Mycteroperca*	*tigris*
	Epinephelus	*striatus*
	Epinephelus	*itajara*
	Mycteroperca	*bonaci*
	Cephalopholis	*cruentatus*
	Cephalopholis	*fulva*
	Hypoplectrus	*puella*
	Hypoplectrus	*indigo*
Sparidae	*Calamus*	*calamus*
Sphyraenidae	*Sphyraena*	*barracuda*
Tetraodontidae	*Canthigaster*	*rostrata*

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