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Abstract

Citizen science can increase the scope of research in the marine environment; however it suffers from necessitating specialized training and simplified methodologies that reduce the output of research. This paper presents a simplified, novel survey methodology for citizen scientists, which combines GoPro imagery and structure from motion to construct an ortho-corrected 3D model of habitats for analysis. These results were compared to surveys conducted with traditional snorkelling methods for benthic cover, holothurian counts, and coral health. Results were comparable between the two methods, and structure from motion allows the results to be analysed off-site for any chosen visual analysis. The GoPro method outlined in this study is thus an effective tool for citizen science in the marine environment, especially for comparing changes in coral cover or volume over time.

Introduction

The assessment of habitats to understand the demography of animal and plant distributions in relation to perturbations is a central theme in ecology (Guisan and Zimmermann 2000). Such analyses rely heavily on accurate spatial resolution of habitats and their inhabitants to generate ecologically relevant predictive hypotheses on community drivers. While accurate spatial

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methodologies have been generated for terrestrial habitats(Belay et al. 2015), assessments of aquatic habitats are often confounded due to the difficulties of examining large areas under water (Leonardsson et al. 2016), causing researchers to focus on predictive modelling rather than surveying (Rengstorf et al. 2013).

Aquatic habitats of particular concern are coral reefs, which are under threat from multiple anthropogenic sources (Smith et al. 2013). Such threats include warming waters (Doney et al. 2012), ocean acidification (Hooidonk et al. 2014), eutrophication/pollution (Jessen et al. 2013; Koop et al. 2001), and overfishing (Loh et al. 2015). As a result, accurate and precise large-scale assessments of global health, growth and diversity of coral reef habitats are necessary to further assess and monitor such impacts. Assessments require repeated and widespread reef habitat surveys, which have traditionally been done using trained snorkelers (De'ath et al. 2012). As global assessments of such habitats are too time-intensive and costly to be done by any single research group, large scale data are preferentially obtained through the expansion of citizen science whenever possible (Dickinson et al. 2012; Dickinson et al. 2010; Foster-Smith and Evans 2003).

Citizen science generally refers to scientific research done in part or in whole by collaborators that lack credentials or formal training in the area of expertise (Cohn 2008). While the practice of using collaborators for science is not new, the process has expanded to less specialised collaborators substantially since the 1990s with the wider adoption of the internet, which has simplified information exchange over broader scales (Dickinson et al. 2010). One of the primary issues with citizen science is the need for ongoing training of the collaborators, without which the quality of the data generally suffers (Dickinson et al. 2012). Methodologies that are simplified are thus more reliable and more likely to produce rigorous datasets as they require less training. Citizen science initiatives with basic methodologies, such as CoralWatch (Marshall et al. 2012), are successful because individuals are only asked to match coral colours to a supplied colour chart and do not need to make subjective decisions based on prior knowledge of the system. Despite their success, however, such simplified methodologies often have inherently fewer variables than studies exclusively performed by scientists. A citizen science approach that still captures large amounts of accurate data, therefore, would be beneficial.

Over the last few decades, researchers have been streamlining reef surveying techniques by using novel technologies such as video or photographic analysis of data (Lam et al. 2006; Parker Jr et al. 1994; Rogers and Miller 2001). These techniques are generally expensive, requiring specialised video equipment, and rely on experienced divers and snorkelers. More recently, low-cost action cameras that have depth tolerances equal to or below that of recreational diving have become highly popular, the most prominent of which is the GoPro™, which sold over five million units in 2014. Due to their relative ease of use and high resolution/low cost ratio (Gintert et al. 2012), a number of novel methodologies that use action cameras for marine research have emerged (Assis et al. 2013; Harasti et al. 2014; Letessier et al. 2015). Analysing video footage for scientific purposes, however, remains time consuming and generally requires expert examination of each frame of video.

Structure from motion (SFM) is a novel image analysis technique that allows accurate three-dimensional models and textures to be calculated from a video or series of two-dimensional photos (Westoby et al. 2012). Accurate volume/length measurements can then be taken from the mosaic using photogrammetry: the use of corrected photography as a mapping tool to measure objects within the survey area (Figueira et al. 2015). Traditional applications of photogrammetry are expensive as aircraft are generally used to take the necessary photography. Digital cameras with the requisite resolution have historically been expensive and not widely available. As such, the methodology has largely been constrained to geological surveys with large budgets (Drury and Drury 2001). Recently, however, the proliferation of cheaper high-megapixel cameras, affordable unmanned aerial vehicles, and more powerful personal computers have made SFM/Photogrammetry more widely accessible, allowing its use in diverse fields such as palaeontology (Falkingham et al. 2014), forestry (Bohlin et al. 2012), or fisheries biology (Rohner et al. 2011). Recreational use of these techniques for exploration has been growing, with community projects that include historical shipwreck mapping or modelling of tourist sites. Moreover, there is an increasingly large pool of enthusiasts that have the capabilities to conduct reliable SFM on a variety of subjects, and that have the desire to do so.

This study assesses the use of citizen scientists with GoPros in conjunction with off-site SFM to conduct a typical habitat sampling method for marine ecologists: strip transects (McCormick and Choat 1987). A coral reef flat was used as the test habitat because it is relatively structurally complex in comparison with many other marine habitats, with has distinct mosaics of organisms interspersed in a relatively homogeneous environment, and is commonly sampled using strip transects. We compared our novel sampling regime in this habitat with the traditional snorkel survey technique. A number of commonly used factors were analysed to compare and contrast the two methods: (1) variation in species count of sessile organisms (often used as a measure of biodiversity), (2) variation in benthic cover of corals and macroalgae, (3) mean abundance of holothurians (used here as an indication of resolution), (4) applicability of use within the CoralWatch reef health surveying program (Marshall et al. 2012), (5) time taken to perform each analysis, and (6) the rate of learning the methodology for new citizen scientists.

Materials and Methods

Study site

This research was conducted under Great Barrier Reef marine Park Permit number QC14/004. Surveying was done at the southern reef flats on Heron Island (23.4420'S, 151.9140'E), a coral cay at the southern end of the Great Barrier Reef, Australia. This reef flat is characterised by patchy sand, coral and algal communities, and is isolated from the ocean during low tide (Vacher and Quinn 1997). Data collection occurred from 29/03/15 to 3/04/15 during mid to high tides when water was sufficiently deep to snorkel (1-2m depth). Southern Heron reef flat has been studied extensively, and at that time of the year is dominated by the coral genus *Acropora* (Santos et al. 2011)*,* and the macroalgal species *Padina gymnospora, Caulerpa racemose clavifera* and *Sargassum polycystum* (Cribb 1966; Scopélitis et al. 2011).

Snorkel surveys

Twelve transects were haphazardly placed around the reef flat to compare surveys that used GoPro cameras and traditional snorkel methods. Transects were 50m long and 2m wide, or approximately $100m^2$, and were separated by at least 50m. Each transect was surveyed twice (one benthic survey, one holothurian survey: these two surveys were separated to simplify the process for snorkelers, though experienced surveyors could easily conduct both at once in other circumstances) by five independent snorkelers who had taken a two-day course on snorkel safety and coral/algae identification, similar to training courses for prospective citizen scientists (Foster-Smith and Evans 2003). Traditional snorkel surveys (Hill and Wilkinson 2004) were done alternated to before or after GoPro recording to reduce any bias of remembering habitat composition.

Gopro photogrammetry/structure from motion surveying

GoPro transects were surveyed only once. To ensure comprehensive coverage of the area, one snorkeler covered the transect area twice (the length of the transect and back) using a GoPro Hero 3 Black™ that was set to continually capture images at maximum resolution at 2Hz (0.5 images per second setting). Snorkelling was done at a slow pace with the arm holding the GoPro outstretched close to the surface and the GoPro aimed straight down at the substrate. The aim was to get over 60% overlap from pictures to ensure they could be aligned, and preliminary testing indicated this method decreased alignment errors over single passes or higher image intervals. GoPro transects were done towards high tides when possible to increase the area of the GoPro's coverage.

Image analysis

An orthocorrect (with corrected distances between points) 3D textured model that could be used to conduct virtual surveys through structure from motion and photogrammetry was created (Falkingham et al. 2014; Westoby et al. 2012). Images for each transect were compiled using Agisoft Photoscan (Agisoft LLC), a 3D rendering program that can build point meshes and orthomosaics from digital photos. High complexity depth maps were reconstructed from a point map, where the orientation of the mesh was established (approximately 1,000,000 polygons). Photographic textures were then laid over the mesh, and a high-quality orthomosaic was computed. The resulting TIFF files were approximately 60,000 x 20,000 pixels (a resolution of 0.3mm per pixel). The required inputs required to produce such an image only include selecting the images and the appropriate analyses (under 5 minutes to conduct), however, processing time can vary greatly depending on the photograph content and the processing power of the computer.

Benthic survey

The benthic survey estimated bommie cover, biodiversity of corals (to genus) and macroalgae (to species). A preliminary survey allowed the reliable identification of predominant macroalgal species, and corals were identified to genus using the CoralFinder (a waterproof coral identification handbook) (Kelley 2009) and *a priori* training. Training was considered complete when snorkelers consistently identified corals to the same genus. Using the CoralFinder's ruler as a reference during snorkelling and the transect line during image analysis, the size of bommies were binned according to approximate minimum radius categories (Marsh et al. 1984): (a) from 20 to 50cm radius, and (b) greater than 50cm radius.

Variance comparisons are often used when comparing different surveying methodologies (Harvey et al. 2004; Watson et al. 2005; Willis et al. 2000). While it is likely that different methods are better at surveying certain aspects of the environment and may result in different means, similar rates of variation indicate that different methods are as reliable and are as likely to produce consistent results. A paired t-test was therefore used to compare mean variance of traditional benthic survey snorkelling and GoPro photogrammetry, with the aim of determining whether GoPro photogrammetry could be used as an alternative technique to snorkel surveys.

Holothurian abundance

Holothurians are a prominent element of shallow tropical sediments between bommies on coral reefs. Counts of holothurians occurring in the transects using both traditional and GoPro methods were done. No attempt was made to separate individuals into species, and abundance was purely a count of the number of individuals observed in a transect. Individuals were included in the transect count if any of their body was visible, thus counts here may be a slight over-estimation of real abundance. As we were using the counts for comparative methods only, this did not matter. A nested ANOVA was used to compare abundance counts between GoPro photogrammetry and traditional snorkel methods, and to also compare counts amongst observers.

Coral health

Coral health assessments are a necessary means of monitoring the progress of anthropogenic impacts on coral reefs (Hodgson 1999). CoralWatch is a global citizen science project that facilitates effective reef management by assessing coral health by using a standardised health chart (Marshall et al. 2012). Coral health is inferred by associating the colour of corals with the presence or absence of symbiotic zooxanthellae, the lack of which is characteristic of stressed or dying coral (Rosenberg et al. 2007). By using the simplified chart, members of the community rather than scientists can assess reefs under their care thus empowering and fast tracking early signs of reef decline.

To assess whether our GoPro photogrammetry methods could be used to assess coral health via CoralWatch, twenty corals were chosen at random along each of the transects and their colours assessed using the standardised chart.. Lightest and darkest colours, as well as coral type (branching, boulder etc.) were recorded for each of the chosen corals as per Siebeck et al. (2008). Corals were assessed using charts on traditional snorkel methods (as per CoralWatch practise) then compared with chart use on the images produced via the GoPro transects. T-tests were used to compare the mean lightest and darkest colour between GoPro photogrammetry transects and snorkel transects.

Sample time comparison

One of our expectations of our GoPro photogrammetry surveying was that the method would reduce time taken in the field as assessments of orthomosaics can be done in a more comfortable lab environment. We predicted that the time to complete GoPro photogrammetry surveys would be lower than that of the traditional snorkelling method. We also predicted that the time to complete traditional snorkelling transects would improve at a greater rate and be longer initially than structure from motion surveys with newly trained citizen scientists because these individuals would need to make taxonomic decisions on site. The time taken to complete transects was recorded using stopwatches to the second. The time taken to complete benthic surveys, holothurian counts and CoralWatch surveys were timed separately for both snorkel surveys and for GoPro photogrammetry for each observer. Observer transect times for each transect were then compared using a generalised linear model to estimate rate of improvement for both methods. A nested ANOVA was used to compare the time to complete each survey between traditional transects and GoPro photogrammetry once improvement effects were corrected. Time taken for image analysis was not included because it is performed exclusively by the computer software and requires no hands-on input. Commencing the analysis itself takes under 5 minutes per transect.

Results

Orthomosaics could be produced from the GoPro surveys. Figure 1 shows an example of an orthomosaic produced from one of the GoPro structure from motion surveys. A supplemental figure 1 is also available for a moving 'flight' over the same transect, but using a high polygon 3D model produced from structure from motion. This method produced approximately 550 12 megapixel images per transect.

Benthic diversity

Mean species diversity of corals and algae was significantly different between the two methods, with snorkel transects showing slightly richer diversity than SFM transects (t = 7.104, *df* = 111, *p*< 0.001). GoPro photogrammetry and traditional snorkel surveys were similarly in their assessments of benthic diversity, as the variance of species diversity was not significantly different between the two (t = 1.605, *df* = 11, *p* = 0.068). While not significant, however, snorkel surveys had a slightly higher degree of variation than structure from movement surveys (Fig. 2).

Benthic cover

Mean bommie cover estimates were not significantly different between snorkelling and GoPro photogrammetry (t = 1.36, *df* = 22, *p* = 0.18). Furthermore, GoPro photogrammetry and traditional snorkel surveys were not significantly different in their assessments of benthic cover, as the variance was not significantly different between the two (t = 0.88, *df* = 11, *p* = 0.199, Fig. 3).

Holothurian abundance

GoPro photogrammetry allowed large counts of holothurians, and estimates of holothurian abundance were not significantly different for the snorkel transects or the GoPro photogrammetry transects (f = 4.253, *df* = 1, *p* = 0.042, Fig 4).

Coral health

Using the CoralWatch health chart, GoPro photogrammetry transects were significantly darker than snorkel transects for the lighter colours (t = 7.89, *df* = 59, *p* < 0.001). There was no significant difference between GoPro photogrammetry and snorkel transects for the darker corals (t = 1.98, *df* = 118, *p* = 0.15, Fig. 5).

Time taken

Structure from motion transects took significantly less time to complete in the field than snorkel transects (f = 17.12, *df* = 1, $p < 0.001$). There were no significant differences in mean transect times between observers (f = 1.33, *df* = 4, $p = 0.26$), however, snorkel transects appeared to have a larger number of outliers with high times to complete. While mean transect times were significantly lower for SFM transects, the rate of improvement over time was significantly higher for traditional snorkel transects (W = 15.97, *df* = 1, $p < 0.001$, Fig. 6). Both methods had an asymptotic improvement trend, and the rate of improvement was appeared to be very low or null after the 12th replicate (Fig. 6).

Discussion

Structure from motion transects created using GoPro imagery were successfully used to estimate a host of variables that are often measured using traditional snorkelling. The variability within the results were similar using both techniques, suggesting that structure from motion transects are as reliable as traditional snorkelling. This suggests that benthic transects conducted using GoPro and analysed through SFM are a viable alternative to traditional snorkel transects for citizen science.

Both GoPro photogrammetry and traditional snorkelling had strengths and weaknesses: while variances were not significantly different, measured benthic (coral and macroalgal) diversity estimates were significantly lower when using GoPro photogrammetry, possibly because of the limited resolution of the images. Doubling the image resolution (0.15 pixels per mm) may solve this issue, as it would quadruple image size. This would, however, result in more computer resource use during analysis. Despite the limited ability of structure from motion for the identification of coral polyps (due to limited image resolution), estimates of benthic diversity were as reliable using structure as from traditional snorkelling.

Counts of holothurian abundance were not significantly different between traditional snorkelling and GoPro photogrammetry methods. Methodology in our photogrammetry method could be improved, however: studies that count holothurian abundance/diversity should amend the method to use a slow sweeping recording motion using varied GoPro angles to ensure that the areas below corals are effectively covered. Structure from motion algorithms remove 'moving points' (i.e. fish or other animals that move at a respectable pace) from images as aberrations, and it is possible the detectability of some holothurians was greatly reduced during image analysis as a result.

Health assessments of coral reefs using the prescribed CoralWatch method and using GoPro photogrammetry were skewed towards the darker colour spectrum in comparison to snorkel surveys. Studies that rely on colour spectrums may need to take precautions should they wish to use GoPro photogrammetry. Colour differences between GoPro photogrammetry methods and snorkel surveys could be corrected via data transformation (colours were skewed by a mean of 0.43 points) or via image colour correction. Colour correction should also be considered if colour is a variable that may influence data analysis, especially on darker sampling days or at greater depths. Blue-shift can be corrected either with a red filter on the camera itself (currently available for GoPros) or with image post-processing software such as Adobe Photoshop that include auto-colour correction functions.

While structure from motion surveys were significantly faster to complete than traditional snorkelling methods, these analyses did not include the time taken to enter images into analysis programs or the processing time. User-end time-to-complete is likely similar between the two methods (selecting the images for processing only takes a few minutes), but computer processing time can vary from a few minutes to a few hours but would depend on the complexity of the images, the ease of alignment, and the resolution of the images. Learning curves were slower for this method than for traditional methods; however, after twelve surveys any time differences between the two methods were negligible. These results can be explained by the necessary multitasking required of inexperienced snorkelers that need to learn the difficulties of correct identification and record-keeping in the marine environment that are not present during our structure from motion analysis sampling methodology. Traditional methods require the snorkeler to observe, identify and/or count, and to scribe their data, whereas those using the structure from motion method merely focus on correct camera techniques. These results suggest that newer collaborators can become proficient in the analysis of structure from motion surveys at a fast rate and with less difficulty than in traditional methods, and that these two methods take similar amounts of time to perform.

Structure from motion analysis from our GoPro technique has benefits among citizen science methodologies for assessing coral reefs in that it can be simplified for non-scientists and allows numerous, accurate assessments for the end-user once the images are processed. Traditional surveys require dive slates, identification guides, and substantial initial training to ensure consistency, whereas GoPro/SFM only requires an action camera, orthogrammic measurements for any reference objects in the imagery, and a simple set of instructions that require minimal to no training. Results can be uploaded to the internet using cloud computing and analysed separately by one or multiple end-users for any desired purpose. It is also possible for citizen scientists to conduct the SFM transformation themselves, but this is a more complex process that requires some online training and was not examined in this research. In addition, many coral reefs or indeed any analogous aquatic benthic habitat, can be assessed over a brief period of time on a regional to global scale using this method, thus allowing for broad geographic scale assessments of habitat and the opportunity to build a temporal database of specific sites that could be readily accessible to a range of scientists and projects in the future.

Unlike traditional transect methods, SFM allows orthogrammic measurements that are (for this study's dataset) accurate to ± 0.3 mm, enabling users to measure size and growth of corals over time. A recent study found that SFM could reliably be used to measure reef areas to 1-6 mm precision (Figueira et al. 2015). This level of accuracy is not possible using traditional techniques on these scales, especially for citizen science as few other underwater methods provide this level of accuracy for larger measurements. Laser scanning has been used in the marine environment but is too complex/expensive for citizen science (McKinnon et al. 2011).

Video and camera imagery are more reliable for detecting changes over time than visual surveying (Ninio et al. 2003). Furthermore, structure from motion and photogrammetry allows accurate calculations of coral volume (McKinnon et al. 2011), and researchers could theoretically measure increases and decreases in particular attributes of a habitat that they have never visited in person. For example, if a researcher wished to monitor a reef over time, or assess the impacts of pollution/extreme weather, they could assess diversity and coral health using the initial orthographic (i.e., figure 1), and then compare these data with a new orthographic constructed after a survey of the same reef. They could then measure coral volume changes by comparing the 3D meshes produced from both transects. Results from structure from motion surveys could also be made available to the public for other uses, which may include historical reference to form the baselines of future studies and/or educational purposes.

Future studies considering using this methodology should be addressed address the following considerations a priori, especially image overlap/resolution and colour correction. Structure from motion requires substantial overlap (>60%) between images for successful alignment (Jebara et al. 1999; Torr and Zisserman 2000). Assuming the rate of movement of a snorkeler is limited, the limiting factor for data sets is therefore the depth of the area surveyed. Shallow reefs (< 2m depth) such as the ones in this study require a high image capture rate (2Hz) to achieve >60% overlap. Due to the increased area covered by the objective, deeper reefs require lower capture rates. Fewer images per square metre also result in smaller total data throughput, which suggests that transects conducted in deeper waters can cover much larger areas without creating bottlenecks in data analyses (analysing over 1000 12 megapixel images can use over 32Gb of RAM, more than the majority of current-generation PCs). The trade-off for deeper reefs would be lowered resolution and greater blue-shift. Surveying from 4 m depth rather than 2 m would quadruple the area covered but lower the resolution by a factor of four, for instance. Given that the maximum resolution achieved at 2 m was only 0.3 mm per pixel, however, lowered resolution is unlikely to be detrimental unless much deeper depths-from-substrate are considered. The issue of maximum resolution may be resolved over time when higher megapixel cameras become available. For transects conducted at greater depths by divers or by remote-underwater-vehicles, users should determine what the end-desired resolution should be (e.g. coral polyps vs. coral volume) and adjust depth-from-substrate accordingly.

One aspect that may separate the two methods is cost. While the initial setup of a GoPro analysis lab is not insignificant (~$3000 AUD computer, data storage capability, staff to process and analyse transects, program license of $3500 AUD for Agisoft Photoscan though open-access software is available), the benefits of not requiring off-site staff training would quickly recoup the initial costs. Assuming we were tasked with training citizen scientists for traditional snorkelling techniques at the same area we conducted this project (not remote from the Sydney area where the trainers were based), it would take less than six training trips to recoup the costs compared to GoPro citizen science. If surveys are required in remote locations, or over large areas, or over long time-scales, the alternative method presented in this study becomes even more financially viable.

Results of this study suggest that the use of GoPros and structure from motion are reliable for citizen science for assessing sedentary organisms on coral reef habitats. There is a high probability that this our GoPro photogrammetry method will also work successfully in other analogous aquatic habitats but this is still to be tested. Our methodology is comparatively low-cost and can be simplified for citizen scientists, yet still allows highly accurate data collection and analyses. Structure from motion is a recent analysis technique limited by current computing power, and the analysis of larger data sets at greater speed will become simpler as more powerful computers and higher resolution action cameras become widely available. The digital nature of the data produced allows for the distribution of the results to a wide research audience for a variety of possible uses.

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1

Example of transect produced using GoPro structure from motion

Here is an example of one of the transects in this study constructed using GoPro structure from motion. Note that the resolution of the source file has been greatly lowered to make it more accessible: the original file had a resolution of 60,000 x 10,000 pixels and a size of ~50mb.

Figure 2(on next page)

Mean benthic diversity per transect

Species diversity box plots comparing traditional snorkelling and GoPro photogrammetry

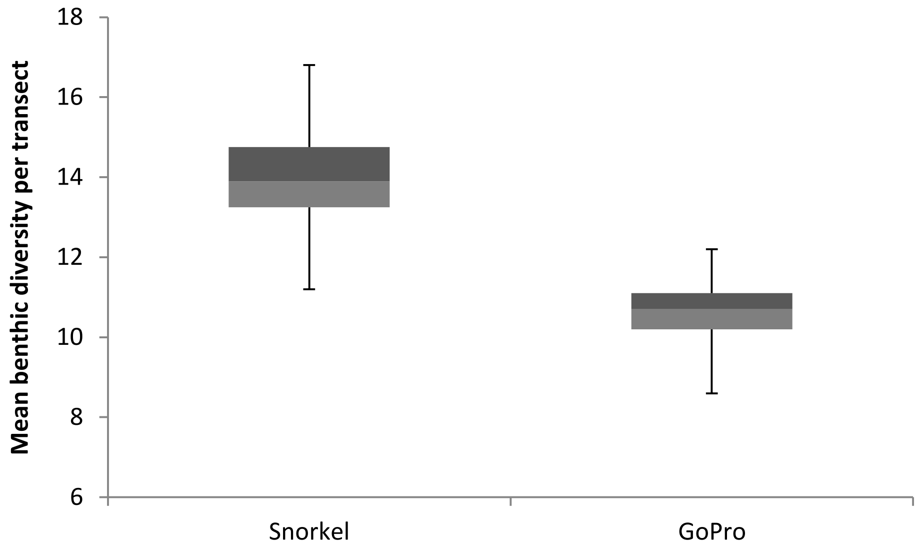

Mean benthic diversity per transect
18
16
14
12
10
8
6
Snorkel
GoPro

Figure 3(on next page)

Mean benthic cover per transect

Benthic cover (coral bommies) box plots comparing results from traditional snorkel surveys from GoPro photogrammetry.

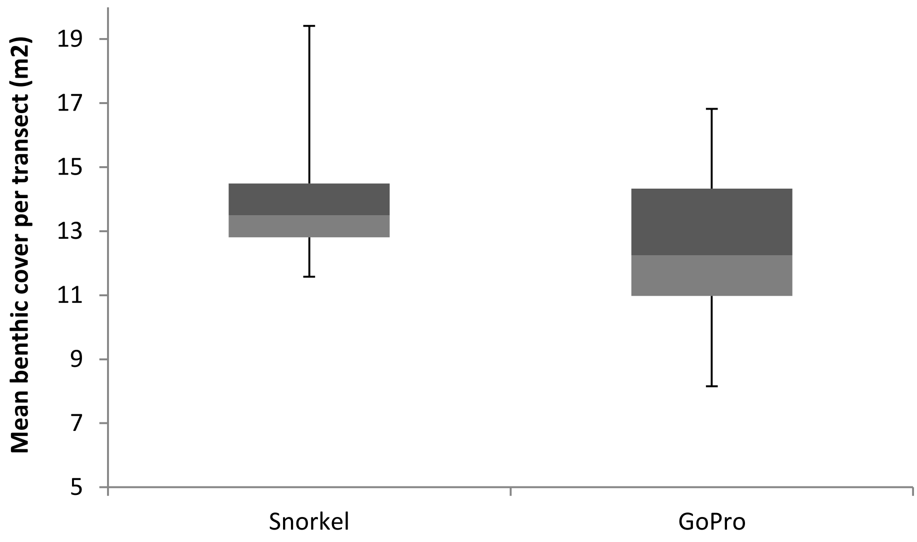
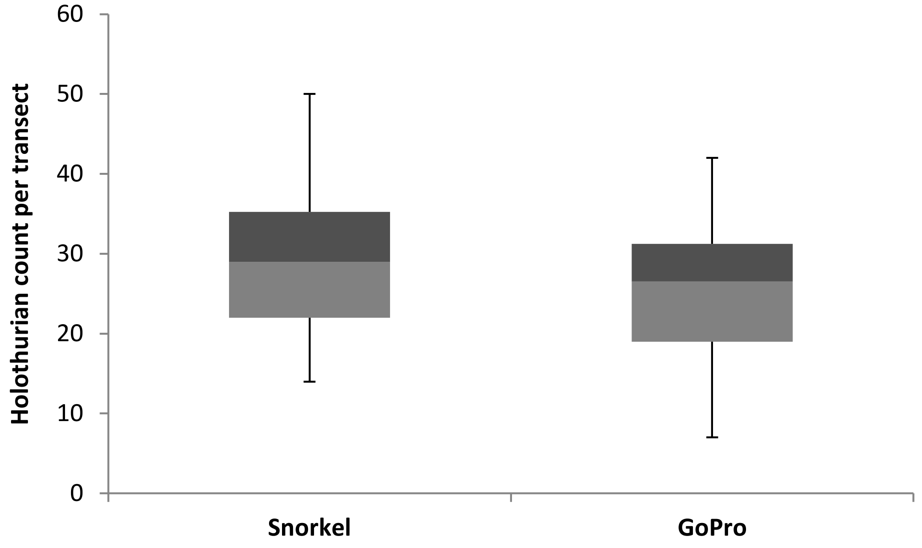

Mean benthic cover per transect (m2)
19
17
15
13
11
9
7
5
Snorkel
GoPro

Figure 4 (on next page)

Mean holothurian count per transect

Mean holothurian count per transect box plot, comparing snorkel and GoPro structure from motion.



60
50
40
30
20
10
0
Holothurian count per transect
Snorkel
GoPro

Figure 5(on next page)

Mean Coralwatch values

Mean ± 1. S.E. lightest and darkest CoralWatch colour chart results using either traditional snorkel surveys or GoPro photogrammetry. Asterisks represent means that are significantly different.

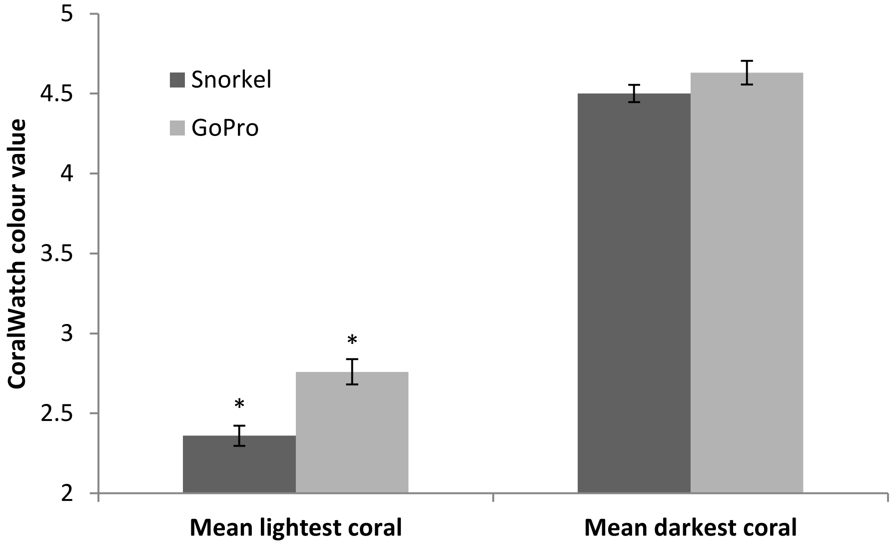
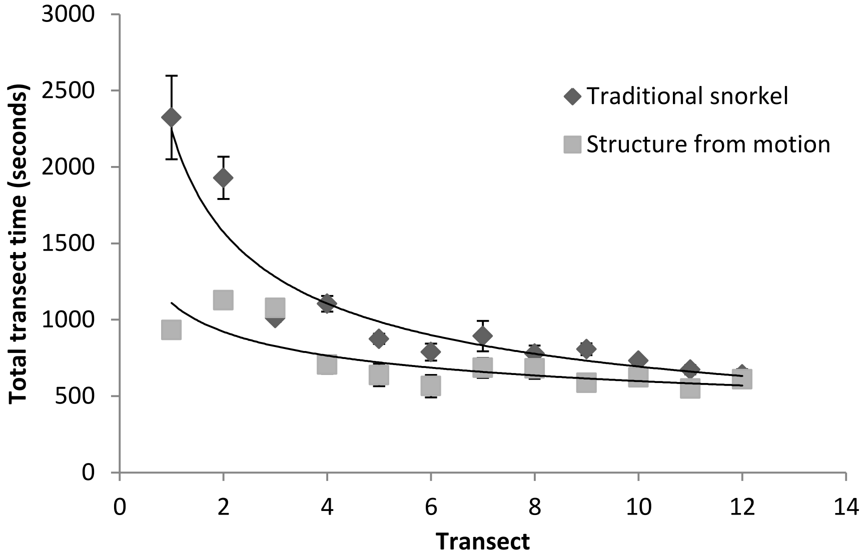

5
4.5
4
3.5
3
2.5
2
CoralWatch colour value
Snorkel
GoPro
*
*
Mean lightest coral
Mean darkest coral

Figure 6(on next page)

Mean time taken per transect

Mean ± 1 S.E. time taken per transect across the five observers and between traditional snorkel surveys and GoPro photogrammetry.


Traditional snorkel
Structure from motion
Total transect time (seconds)
Transect
0
500
1000
1500
2000
2500
3000
0
2
4
6
8
10
12
14