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2017

Original citation:

Bryant, D. E. P., Rodriguez-Ramirez, A., Phinn, S., González-Rivero, M., Brown, K. T., Neal, B. P., Hoegh-Guldberg, O., & Dove, S. (2017). Comparison of two photographic methodologies for collecting and analyzing the condition of coral reef ecosystems. *Ecosphere, 8(10)*. https://doi.org/10.1002/ecs2.1971 esa ECOSPHERE

EMERGING TECHNOLOGIES

Comparison of two photographic methodologies for collecting and analyzing the condition of coral reef ecosystems

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Citation: Bryant, D. E. P., A. Rodriguez-Ramirez, S. Phinn, M. González-Rivero, K. T. Brown, B. P. Neal, O. Hoegh-Guldberg, and S. Dove. 2017. Comparison of two photographic methodologies for collecting and analyzing the condition of coral reef ecosystems. Ecosphere 8(10):e01971. 10.1002/ecs2.1971

Abstract. Coral reefs are declining rapidly in response to unprecedented rates of environmental change. Rapid and scalable measurements of how benthic ecosystems are responding to these changes are critically important. Recent technological developments associated with the XL Catlin Seaview Survey have begun to provide high-resolution 1-m^2 photographic quadrats of ~1.8–2 km of coral reefs at 10 m depth by using a semi-autonomous image collection SeaView II camera system (SVII). The rapid collection of images by SVII can result in images being taken at a variable distance (1–2 m) from the substrate as well as having natural light variability between images captured. This variability can affect the quality of taxonomic resolution archived from photographic quadrats captured by SVII. Conventional approaches for taking photographic quadrats of coral reefs involve taking images from a fixed distance with the use of artificial light. These methods often provide images that enable high taxonomic resolution, but are typically used to cover areas of 50–150 m. Here, we select key metrics associated with coral reef condition from a functional perspective to contrast how much is lost in terms of association and agreement from image annotations using SVII images (1-m^2 photoquadrats) compared to conventional methods, capturing 0.5-m^2 photoquadrats using a digital single lens reflex camera from a fixed height of 0.5 m above the benthos. Comparisons were made over the same 50-m linear transects at 15 sites in the Maldives. Photoquadrats were manually analyzed using an online image annotation tool and image repository called coral net with 25 randomly placed dots per 0.5 m^2 of a quadrat. Our results reveal high levels of correlation and agreement between methods when measuring the abundance of hard corals as a functional group and individual labels, which make up hard corals as a functional group. These results demonstrate the two methods are comparable when measuring functional groups and coral communities on coral reefs. Therefore, involving rapid semi-automated technologies that maximize data collection for monitoring coral reefs does not necessarily imply that taxonomic resolution is compromised. This insight has important ramifications for detecting important changes in coral reef condition, such as a decline in coral cover or shifts in benthic community composition.

Key words: benthic assessment; coral reefs; environmental monitoring; image analysis; Maldives; photoquadrats; underwater photography.

Received 23 August 2017; accepted 24 August 2017. Corresponding Editor: Lucas N. Joppa.

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Introduction

Coral reefs are undergoing rapid reduction in hard coral cover (Gardner et al. 2003, Pandolfi et al. 2003, Bruno and Selig 2007, Edmunds and Elahi 2007, De'ath et al. 2012) and shifts in community structure (Gleason 1993, Glynn et al. 2001, Pratchett 2010, Pratchett et al. 2011) in many regions globally. These changes are occurring as a result of climate change (Hoegh-Guldberg et al. 2007) as well as local anthropogenic stressors (Mumby 2006, Williams et al. 2015). The increased frequency and severity of disturbances such as cyclones, coral bleaching events, *Acanthaster planci* (crown-of-thorns starfish, COTS) outbreaks, as well as other impacts from anthropogenic influences, is heralding the need for monitoring these changes in community ecology of coral reefs rapidly and at larger scales (Edmunds and Bruno 1996, Knowlton and Jackson 2008, De'ath et al. 2012, González-Rivero et al. 2014). The XL Catlin Seaview Survey (XL CSS) was launched in 2012 with the aim of developing a broad-scale assessment of the state of key coral reefs around the world (González-Rivero et al. 2014, 2016) and providing a much-needed standardized global baseline (Knowlton and Jackson 2008, Trygonis and Sini 2012) that is rapid, accurate, and rigorous.

Previous attempts to assess the condition of benthic communities on coral reefs vary in spatial scale and taxonomic resolution (Fig. 1; Andréfouët et al. 2002, Mumby and Steneck 2008, Hedley et al. 2012, González-Rivero et al. 2014). Satellite imagery and airborne photography (Fig. 1d, e) provide remote sensing at scales of 1–1000 km of reef surveyed enabling the construction of coarse habitat boundary maps that provide information on percent cover for simple categories of benthos (e.g., living vs. dead coral cover, macroalgae, and soft sediment; Mumby et al. 1997, Hochberg and Atkinson 2003, Mumby et al. 2004). Furthermore, in-water surveys must be performed in order to allow for object-based image analysis within the photographs collected (Phinn 1998, Mumby et al. 1999, Roelfsema et al. 2010, Phinn et al. 2012). This reduction in detail and taxonomic resolution means scientists and decision makers miss out on useful information such as changes in the diversity and community structure of coral reefs. Being able to measure the frequency and

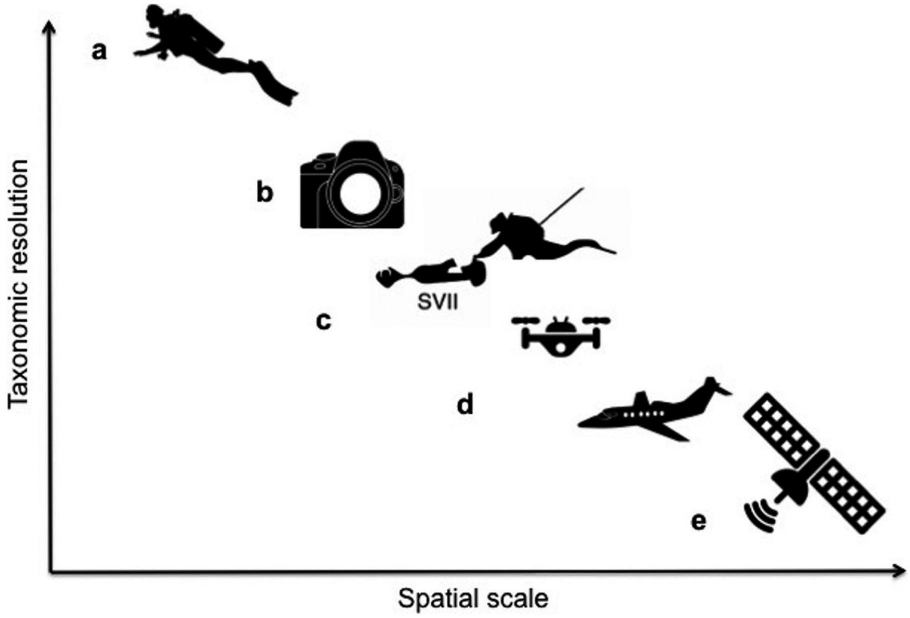

Fig. 1. Coral reef survey technique differences in spatial scale and taxonomic resolution. (a) In situ diver assessment, (b) high-resolution photoquadrats (0.25–1 m^2), (c) SVII with diver propulsion vehicle, (d) airborne photography (aircraft and drone), and (e) satellite imagery.

abundance of the key organisms is essential if we are to broaden our understanding of the drivers and resulting changes to the world's coral reefs (Knowlton and Jackson 2008). On the other hand, in-water diver assessment techniques (Fig. 1a) offer the highest level of taxonomic resolution. The time, cost, and effort for in-water diver assessment techniques, however, reduce the ability to cover large spatial scales (i.e., 50- to 200-m SCUBA dive; Mumby et al. 1999, Hill and Wilkinson 2004). Therefore, remote sensing techniques (Fig. 1d, e), or diver surveys based on the rapid collection of imagery (e.g., video or semi-autonomous photography; Fig. 1b, c), offer a cost-effective monitoring technique for rapidly measuring the state of coral reefs at larger scales (González-Rivero et al. 2014).

Recent advances in photography, computer learning, and image classification have increased the scale over which measurements with a high degree of precision and accuracy can be made. The XL CSS utilizes an innovative camera assemblage (SeaView II or SVII camera) which is made up of a high-resolution 360° panoramic camera system connected to a diver propulsion vehicle (DPV). This technology has opened up new possibilities for understanding reef ecosystems at multiple kilometer scales, at a depth of 8–12 m (González-Rivero et al. 2014). The SVII has the ability to collect and analyze over a thousand images per 1.5- to 2-km transect, which would otherwise take a large amount of time and cost using conventional human-based methods. Furthermore, surveys performed without a DPV become nearly impossible in areas with strong currents (González-Rivero et al. 2014, 2016).

Semi- and fully automated underwater vehicles (AUVs) are increasingly being used for the collection of large image sets that archive taxonomic information of benthic marine habitats (Durrant and Dunbabin 2011, Williams et al. 2012, González-Rivero et al. 2014, Roelfsema et al. 2015). Although AUVs offer advantages in terms of the amount of data collected, there are limitations when using certain types of uncontrolled photography that can introduce error into the quality of the data collected due to a reduction in image quality within the image set. This error can be attributed to factors such as changes in light availability, changes in the distance an image is taken from the benthos, and changes in attitude (i.e., pitch, yaw, and roll) that an image was taken (González-Rivero et al. 2014).

The research described here aimed to select key metrics associated with coral reef condition from a functional perspective and contrast how much is lost in terms of association and agreement between image annotations using a semi-autonomous image collection method (SVII camera system) and a more conventional method, which offers more consistent image quality at the cost of spatial scale. Exploring the capabilities of a semi-autonomous AUV methodology to provide similar or better association and agreement at larger spatial scales is an important step in developing the capacity to make broad-scale interpretations regarding coral reef conditions during unprecedented rates of decline (Edmunds and Bruno 1996, Balmford et al. 2005, Edmunds and Elahi 2007, Knowlton and Jackson 2008, De'ath et al. 2012, González-Rivero et al. 2014).

MATERIALS AND METHODS

Image collection

Images were collected during the 2015 XL Catlin SS Maldives expedition from the 30th of March to the 19th of April 2015. Fifteen of the sites from the expedition were chosen to explore the agreement and performance of the two methods (Fig. 2). A 50-m transect tape was laid out at a depth of 10 m at the starting point of each of the 1.5- to 2-km SVII transects (Fig. 4e).

SVII method

The SVII camera system (Fig. 4a) is a customized high-resolution imaging system (González-Rivero et al. 2014) approximately 2 m in length and 50 kg in weight. The SVII houses three remotely triggered digital single lens reflex Canon 5d MkII cameras (Canon Inc., Tokyo, Japan; maximum resolution = 5613 × 3744 mpixels), which have been aligned in a housing designed to capture a 360° panoramic of the surrounding environment every three seconds. The camera housing is attached to a DPV, allowing the diver to cover up to 2 km per dive. A fisheye lens with the aperture set to f8 is connected to the camera, and ambient light is used in order to preserve battery power. The SVII diver can change the ISO and shutter speed manually via a Samsung

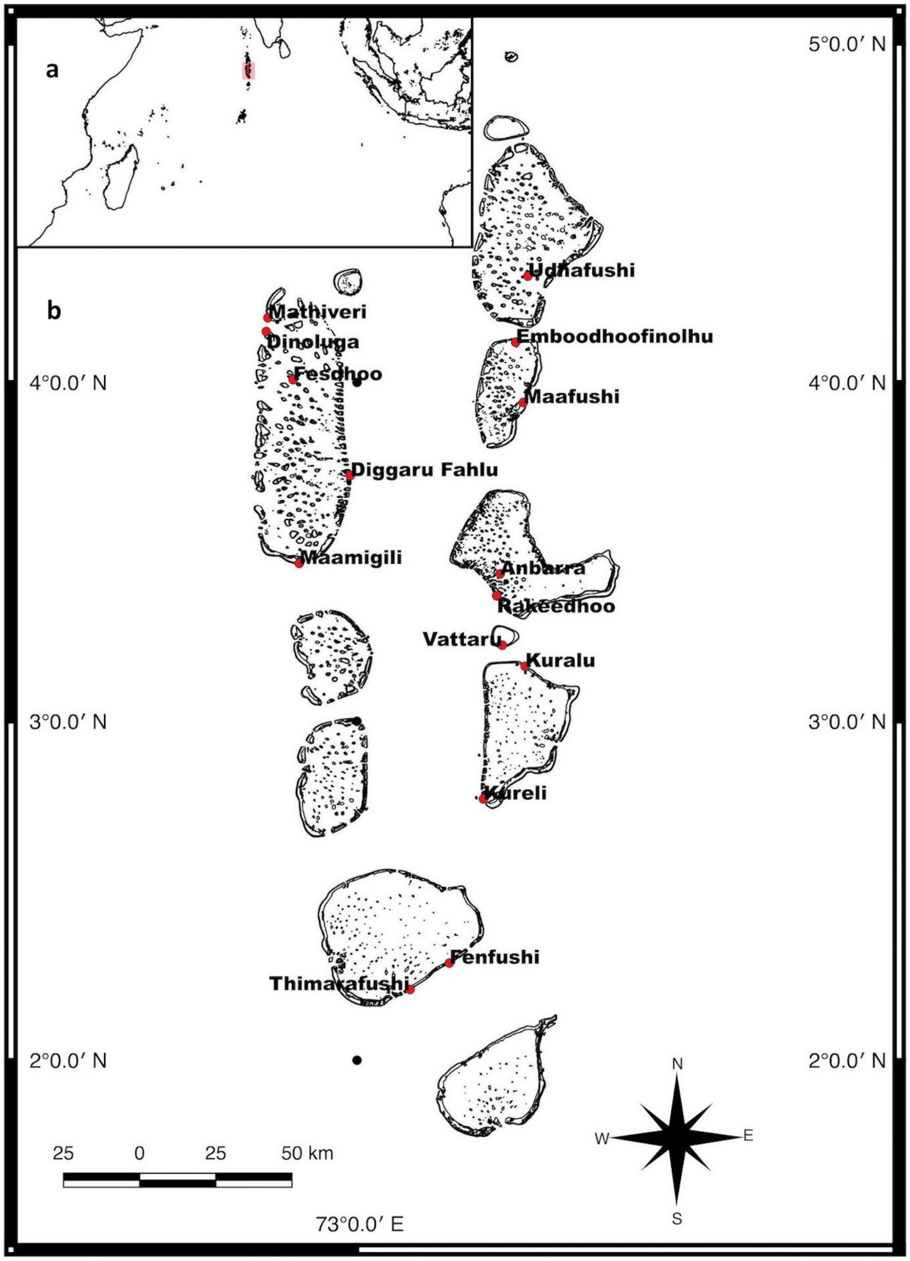

Fig. 2. Map of survey sites for comparison of SVII and conventional photoquadrat methods in the Maldives taken during the March–April–2015 XL Catlin Seaview Survey expedition. (a) Map of the Indian Ocean with the survey area of the Central Maldives highlighted in red. (b) Survey sites in the Central Maldives.

Galaxy tablet connected to the top of SVII. The diver has the ability to view each image on the Samsung Galaxy tablet screen and will make adjustments to ISO according to light availability. The shutter speed is maintained at 1/320 due to the propulsion of the SVII while taking images. For more details regarding SVII and its use, refer to González-Rivero et al. (2014).

SVII captured images over a 50-m transect at 10 m depth to compare with conventional methods in ~1–2 minutes depending on current conditions. Photoquadrats of 1 m^2, with an average resolution of 20 and 10 pixels/cm, were color-corrected and then cropped from the SVII images by using a time-stamped altitude measurement taken from a Micron Echosounder altimeter by Tritech (Tritech International, Westhill, Aberdeenshire, UK), attached to the bottom of the DPV body on SVII. A pressure sensor was also used to record the depth each image was captured. Furthermore, a global positioning system, which has been time synchronized with the cameras and sensors, was attached to a surface marker tethered to the SVII diver. Therefore, every image is spatially georeferenced (González-Rivero et al. 2014).

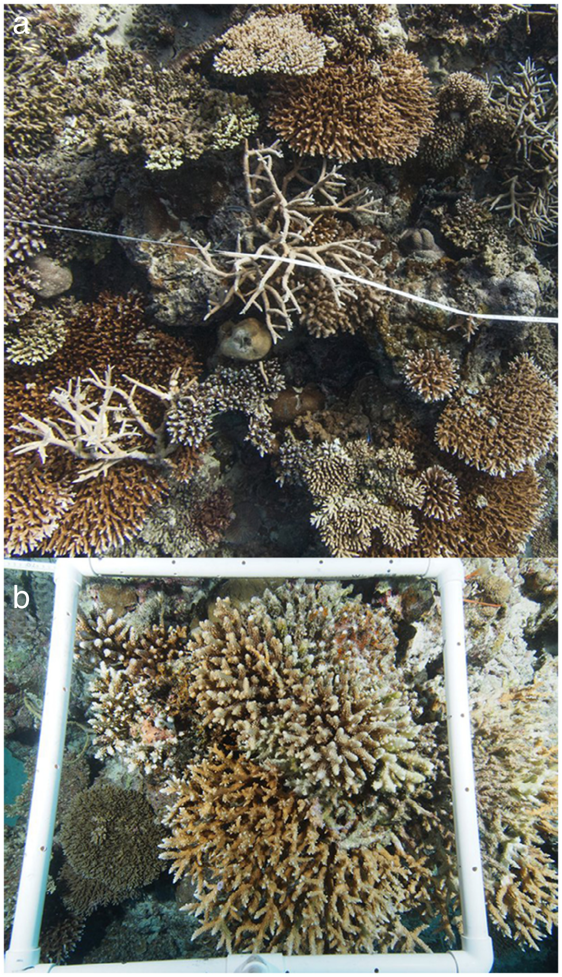

Fig. 3. (a) Cropped and color-corrected SVII 1 × 1 m photoquadrat from Emboodhoofinolhu reef with a full resolution of 1171 × 1171 pixels. (b) Un-color-corrected conventional 0.5 × 0.5 m photoquadrat using two strobes taken at Emboodhoofinolhu reef with a full resolution of 4608 × 3456 pixels.

Between 20 and 40 1-m^2 SVII photographic quadrats (Fig. 3a) were selected from the SVII images at each site (Table 1). A 50-m transect tape running through the center of the image was used to identify which 1-m^2 SVII photographic quadrats were selected for image analysis. SVII photographic quadrats (1 m^2) were assessed to ensure there was no overlap of area between quadrats before being manually annotated on coral net. Differences in the number of 1-m^2 SVII photographic quadrats are caused by the speed the DPV is traveling. Differences in DPV speed can be due to the current at the time and the diver driving the DPV.

Conventional method

Divers used a 0.5 × 0.5 m quadrat attached to Olympus mirrorless EM-5 digital camera (Olympus Corporation, Tokyo, Japan; maximum resolution = 4608 × 3456) at a fixed distance of 0.5 m away from the substrate to take pictures (Fig. 3b) during 60-minute SCUBA dive. Two Sea and Sea YS-D2 strobes were also attached provided artificial light for each image. Between 50 and 90 photographic quadrats (Fig. 3b) were taken using the conventional method on a single 50 × 1 m linear transect (Table 1). On occasion, strong currents and equipment failures caused dives using conventional methods to be abandoned before the 50 m could be completed.

Image annotation and analysis

Images were manually annotated by an expert annotator using CoralNet (Beijbom et al. 2012), an online repository for analyzing coral reef images; 100 randomly allocated points were used for the analysis of each 1-m^2 photoquadrat captured by SVII (Fig. 4b) and 25 points were used for the 0.5-m^2 photoquadrats collected employing conventional methods (Fig. 4d). The number of points was chosen in order to assess relatively the same amount of space inside the photoquadrats from both methods (i.e., 25 points per 0.5 m^2 of photoquadrat). Correlation and agreement between the two methods was explored when estimating label categories made up of (1) broad benthic parameters at a functional level (i.e., dead hard coral, hard coral, macroalgae, and other invertebrates); (2) morphological groups within the hard coral

Table 1. Area covered in m^2 by SVII and conventional methods over the same 50-m linear transects at 15 sites in the Maldives, surveyed during the 2015 XL Catlin Seaview Survey expedition (www.catlinseaviewsurvey.com).

Sites	Latitude/Longitude	No. SVII 1-m^2 quadrats = area covered (m^2)	No. conventional 0.5-m^2 quadrats × 0.25 = area covered (m^2)
Anbarra	3′26.11325 N/73′25.32778 E	30 × 1 = 30	90 × 0.25 = 22.50
Diggaru Fahlu	3′42.80441 N/72′58.88254 E	31 × 1 = 31	58 × 0.25 = 14.50
Dinoluga	4′9.04307 N/72′43.87115 E	30 × 1 = 30	54 × 0.25 = 13.50
Emboodhoofinolhu	4′7.12197 N/73′28.06809 E	30 × 1 = 30	74 × 0.25 = 18.50
Fenfushi	2′17.28663 N/73′16.41937 E	30 × 1 = 30	89 × 0.25 = 22.25
Fesdhoo	4′0.50388 N/72′48.68643 E	30 × 1 = 30	80 × 0.25 = 20.00
Kuralu	3′9.75164 N/73′29.72463 E	39 × 1 = 39	89 × 0.25 = 22.25
Kureli	2′47.02307 N/73′22.10777 E	30 × 1 = 30	87 × 0.25 = 21.75
Maafushi	3′56.73654 N/73′30.00041 E	30 × 1 = 30	90 × 0.25 = 22.50
Maamigili	3′28.00391 N/72′50.1526 E	30 × 1 = 30	80 × 0.25 = 20.00
Mathiveri	4′11.30840 N/72′48.68643 E	22 × 1 = 22	90 × 0.25 = 22.50
Rakeedhoo	3′18.63745 N/73.28.07505 E	30 × 1 = 30	84 × 0.25 = 21.00
Thimarafushi	2′12.60078 N/73′9.45339 E	30 × 1 = 30	89 × 0.25 = 22.25
Udhafushi	4′18.80890 N/73′30.21989 E	30 × 1 = 30	90 × 0.25 = 22.50
Vattaru	3′13.47848 N/73′25.69829 E	36 × 1 = 36	50 × 0.25 = 12.50
Mean (±standard error)		31 × 1 = 31 (0.92)	80 × 0.25 = 20 (0.95)

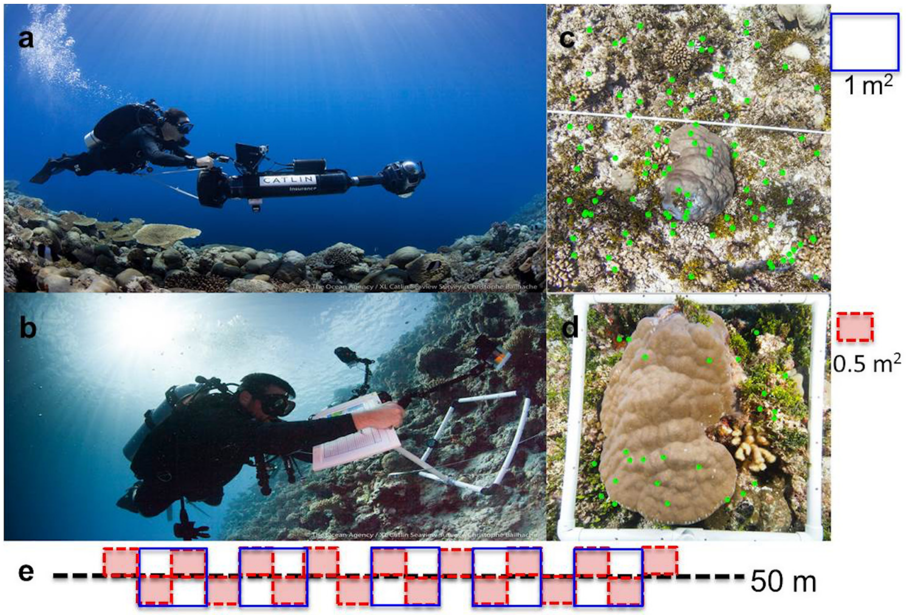

Fig. 4. Methods being compared over 50-m linear transect at 15 sites in the Maldives during the March–April 2015 XL Catlin Seaview Survey expedition. (a) SVII surveying a Maldivian reef slope at 10 m. (b) Cropped and color-corrected 1-m^2 photoquadrat taken from Maafushi using SVII (a) with 100 randomly allocated points using coral net (https://coralnet.ucsd.edu/). (c) Conventional 0.5-m^2 photoquadrats being captured with a 0.5-m stand off the substrate over a 50-m linear transect on a Maldivian reef slope. (d) 0.5-m^2 photoquadrat taken Maafushi using conventional methods (c) with 25 randomly allocated points using coral net (https://coralnet.ucsd.edu/). (e) Illustration of photoquadrat placement over 50-m linear transects in the Maldives, blue squares indicate 1 m^2 from SVII (a), and red squares indicate 0.5-m^2 photoquadrats from conventional methods (b). Images a and c were used with permission from the copyright owners of the Ocean Agency/Christophe Bailhache.

functional group along with genera easily identified based on color and texture from a 2D image (i.e., branching tabulate/corymbose *Acropora,* branching arborescent *Acropora*, branching *Pocillopora*, branching *Porites*, and branching other, massive/submassive/encrusting [MASE] Porites, MASE small invisible polyps, MASE large round polyps, MASE meandering, and thin/foliose/plating [TFP]); and (3) other invertebrates such as soft corals, tunicates, and sponges (Table 2).

Statistical analysis

The percent cover for each quadrat was determined, and then, the average cover per site for each label and functional group was calculated. A D'Agostino and Pearson normality test was performed to check whether the percent cover of each label and functional group for both methods was normally distributed across all 15 sites. If the percent cover for each site was normally distributed, then a Pearson correlation coefficient was performed to measure the strength of relationship between the percent cover estimates of the two methodologies for that specific label or functional group. A Spearman's rank correlation coefficient was determined using GraphPad Prism version 7 (Mac OS X, GraphPad Software, Inc., La Jolla, California, USA) on labels and functional groups that did not pass the D'Agostino and Pearson normality test.

Bland–Altman method comparison plots, commonly used to compare estimation in agreement between two methods of measurement where the true value remains unknown (Bland and Altman 1986, 2003, Giavarina 2015), were constructed to assess agreement between SVII and conventional methods. These methods also give a visualization if one method was biased at estimating coverage of one label over the other. Bland–Altman plot was done by plotting the mean percent cover between the two methods at each site on the x-axis and the ratio between the SVII and conventional methods for each site on the y-axis. If the ratio bias (average ratio across all sites) was more than one, the methods were observed as more biased toward SVII in estimates of benthic cover associated with a specific label or functional group. Ratio bias of less than one meant there were more biases toward conventional methods. Furthermore, an equal proportion of sites scattered on either side of one, and with a ratio closer to one is deemed as suggestive of

Table 2. Label categories and functional groups used for the image annotation of photoquadrats taken using SVII and conventional methodologies on Maldivian reef slopes during the March–April 2015 XL Catlin Seaview Survey expedition (www.catlinseaviewsurvey.com).

Functional group	Label and description
Dead hard coral (DHC)	DHC covered by epilithic algal matrix (EAM)
	Rubble covered by epilithic algal matrix
	DHC covered by crustose coralline algae (CCA)
	Rubble covered by crustose coralline algae (CCA)
	DHC covered by cyanobacteria
	Rubble covered by cyanobacteria
Hard coral	Tabulate/corymbose/plating *Acropora* spp.
	Digitate *Acropora* spp.
	Arborescent *Acropora* spp.
	Branching *Pocillopora* spp.
	Branching *Porites* spp.
	Branching other
	Massive/submassive/encrusting (MASE) *Porites* spp.
	Massive/submassive/encrusting small polyps
	Massive/submassive/encrusting large round polyps
	Massive/submassive/encrusting meandering *Lobophyllia* spp.
	Massive/submassive/encrusting meandering other
	Massive/submassive/encrusting bleached
	Thin/foliose/plating (TFP) with visible relief structures
	Thin/foliose/plating with visible round corallites
Macroalgae	Filamentous macroalgae >1 cm in height
	Leathery macrophytes >1 cm in height
	Halimeda spp. >1 cm in height
Other	Fish
	Transect hardware
	Anthropogenic marine debris
	Unclear (i.e., shadow, overexposed, blurry)
Other invertebrates	*Alcyonacea* spp.
	Crinoids
	Hydroids
	Individual tunicates (*Didemnum molle*)
	Massive or encrusting sponges
	Branching or rope-forming sponges
	Gorgonacea spp. (sea fans and sea whips)
	Mobile invertebrates (echinoderms)
	Other invertebrates (colonial ascidians and hexacorallia)
Soft sediment	Sand

greater method agreement, compared with a lopsided scatter of points more removed from one.

RESULTS

Correlation and agreement of functional groups

Percent cover across all six functional groups surveyed by SVII methods and conventional methods over the 50-m transects at the 15 sites surveyed was significantly correlated. The Bland–Altman method comparison plots depict different ratio bias and agreement between the two methods for percent cover of different functional groups (Fig. 5).

The amount of dead hard coral (DHC) measured by the two methodologies was significantly correlated ($r = 0.9401$, $n = 15$, $P < 0.0001$; Fig. 5a) with a ratio bias of 1.17 and all sites exhibiting a ratio greater than one (Fig. 5b). Estimates of the amount of hard coral cover from the two methodologies were also significantly correlated (Fig. 5c; $r = 0.9527$, $n = 15$, $P < 0.0001$), with a ratio bias of 0.906, with 80% of sites having a ratio of less than one (Fig. 5d).

Macroalgae were significantly correlated, when using a Spearman's rank correlation coefficient (r_s; $r_s = 0.6739$, $n = 15$, $P = 0.0073$; Fig. 5e), and had a ratio bias of 0.58 with 73% of sites having a ratio of less than one (Fig. 5f). Three of the 15 sites (Dinoluga, Feshdhoo, and Vattaru) did not pick up macroalgae using the SVII method, while one site (Diggaru Fahlu) did not find macroalgae using conventional methods. Seventy-three percent of sites had a ratio of less than one. Other (mostly unclear) labels were significantly correlated ($r = 0.641$, $n = 15$, $P = 0.0101$) and had a ratio bias of 1.3 with 66% of the sites having a ratio >1 (Fig. 5h). The benthic category, other

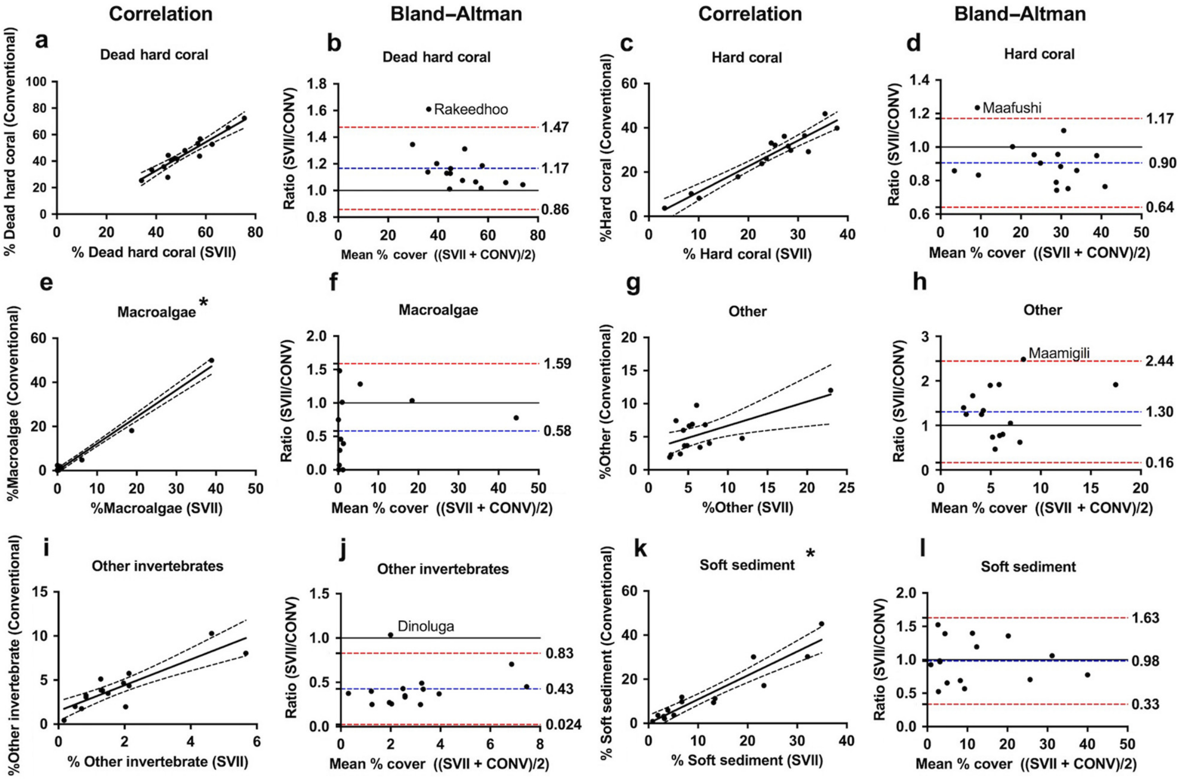

Fig. 5. Correlation (with 95% confidence bands) and Bland–Altman method agreement plots for percent cover of functional groups surveyed by SVII and conventional (CONV methods across 50-m linear transects at 15 coral reef sites from the XL Catlin Seaview Survey Maldives expedition from the 29th of March until the 17th of April 2015). * Indicates Spearman's rank correlation performed for correlation coefficient. Red line indicates 95% limit agreements, and blue line represents ratio bias between SVII and conventional methods for Bland–Altman plots.

invertebrates, was significantly correlated between the two methods ($r = 0.762$, $n = 15$, $P < 0.0001$) with a ratio bias of 0.43 (Fig. 5j) and 93% of the sites having a ratio of less than one. Similarly, the percent cover of sand was significantly correlated ($r_s = 0.9429$, $n = 15$, $P < 0.0001$; Fig. 5k) and had a ratio bias of 0.98 with 53% of sites being under 1 (Fig. 5l).

Correlation and agreement within hard coral functional groups

The percent cover of tabulate/corymbose corals was correlated between methods ($r = 0.9325$, $n = 15$, $P < 0.0001$; Fig. 6a). The ratio bias for tabulate/corymbose corals was 0.91 with 60% of the sites having a ratio of less than one (Fig. 6b). Arborescent *Acropora* was correlated ($r = 0.9004$, $n = 13$, $P < 0.0001$) with a ratio bias of 0.91; however, only 30.7% of the sites had a ratio below one (Fig. 6d). Digitate *Acropora* coral cover was correlated ($r = 0.9063$, $n = 15$, $P < 0.0001$; Fig. 6e) and had a ratio bias of 1.736 (Fig. 6f). A ratio of above one was found in 73.3% of sites (Fig. 7f). Percent *Pocillopora* cover was correlated between the two methods ($r = 0.954$, $n = 14$, $P < 0.0001$; Fig. 6g) with a ratio bias of 0.9229 (Fig. 6h). A ratio of less than one was found in 71.4% of the sites surveyed (Fig. 6h).

The abundance of massive *Porites* was correlated between sites ($r = 0.9312$, $n = 15$, $P < 0.0001$; Fig. 7a) and had a ratio bias of 0.9033 (Fig. 7b). A ratio of less than one was found in 60% of the sites. Massive small/invisible polyps were correlated ($r = 0.7126$, $n = 15$, $P = 0.0029$; Fig. 7c) and had a ratio bias of 1.067. At least 53% of sites had a ratio of less than one between massive small/invisible polyp labels (Fig. 7d). Massive large round polyps corals were correlated ($r_s = 0.9455$, $n = 15$, $P < 0.0001$; Fig. 7e) and had a ratio bias of 0.594 (Fig. 7f). Eighty percent of sites had a ratio of less than one between massive large round polyp labels (Fig. 7f). Massive, meandering corals were correlated ($r = 0.6979$, $n = 15$, $P = 0.0046$; Fig. 8g) and had a ratio bias of 0.8119 (Fig. 7h). A ratio of less than one was found in 66.7% of sites between massive, meandering coral labels (Fig. 7h).

Thin/foliose/plating label (Fig. 8) was analyzed by adding the total percentages of TFP ridged, round polyps and *Porites* labels because the sums of each label alone were too small to conduct an analysis. Estimations of TFP corals between methods were correlated ($r_s = 0.787$, $n = 15$, $P = 0.0009$; Fig. 8a) and had a ratio bias of 0.81 with 63% of sites ratio scattered below one (Fig. 8b).

Correlation and agreement among other invertebrates found in the Maldives

There were three labels from the functional group of "other invertebrates" (i.e., soft corals, solitary tunicates, and massive encrusting sponges) that were identified during annotation and analyzed for the amount of correlation and agreement (Fig. 9). Estimations of soft corals from the *Alcyonaceans* were correlated ($r_s = 0.787$, $n = 15$, $P = 0.009$; Fig. 9a) and had a ratio bias of 1.09 with 55.5% of the sites ratio scattered below one (Fig. 9b). Individual solitary tunicates (i.e., *Didemnum molle*) were correlated ($r_s = 0.7688$, $n = 15$, $P = 0.0013$; Fig. 9), with a ratio bias of 0.34 and 92.3% of the sites with a ratio of less than one (Fig. 9d). Finally, estimation of massive encrusting sponges was not correlated ($r = 0.5231$, $n = 15$, $P = 0.0549$; Fig. 9e) and had a ratio bias of 0.68 with 100% of the sites having a ratio difference of less than one (Fig. 9f).

Discussion

The results presented here provide strong evidence that the two methods explored here are interchangeable. Broad benthic parameters and labels within the hard coral functional group were correlated between SVII and conventional methodologies. These results demonstrate that SVII is a useful tool for rapidly interpreting coral reef conditions and composition (González-Rivero et al. 2014). Although SVII methods cause a slight reduction in taxonomic resolution, by reducing the ability to see organisms <5 cm. Identifying different types of coral categories mentioned in Table 2 are therefore not impeded when using SVII images and it can be done more rapidly and at much larger spatial scale (i.e., 1.5–2 km^2) compared with more conventional in situ survey methods (González-Rivero et al. 2016).

Broad benthic parameters

Functional groups were correlated between methods, indicating that the two methods are estimating similar estimates of the percent cover of broad benthic parameters on coral reefs. However, the SVII method consistently estimated a

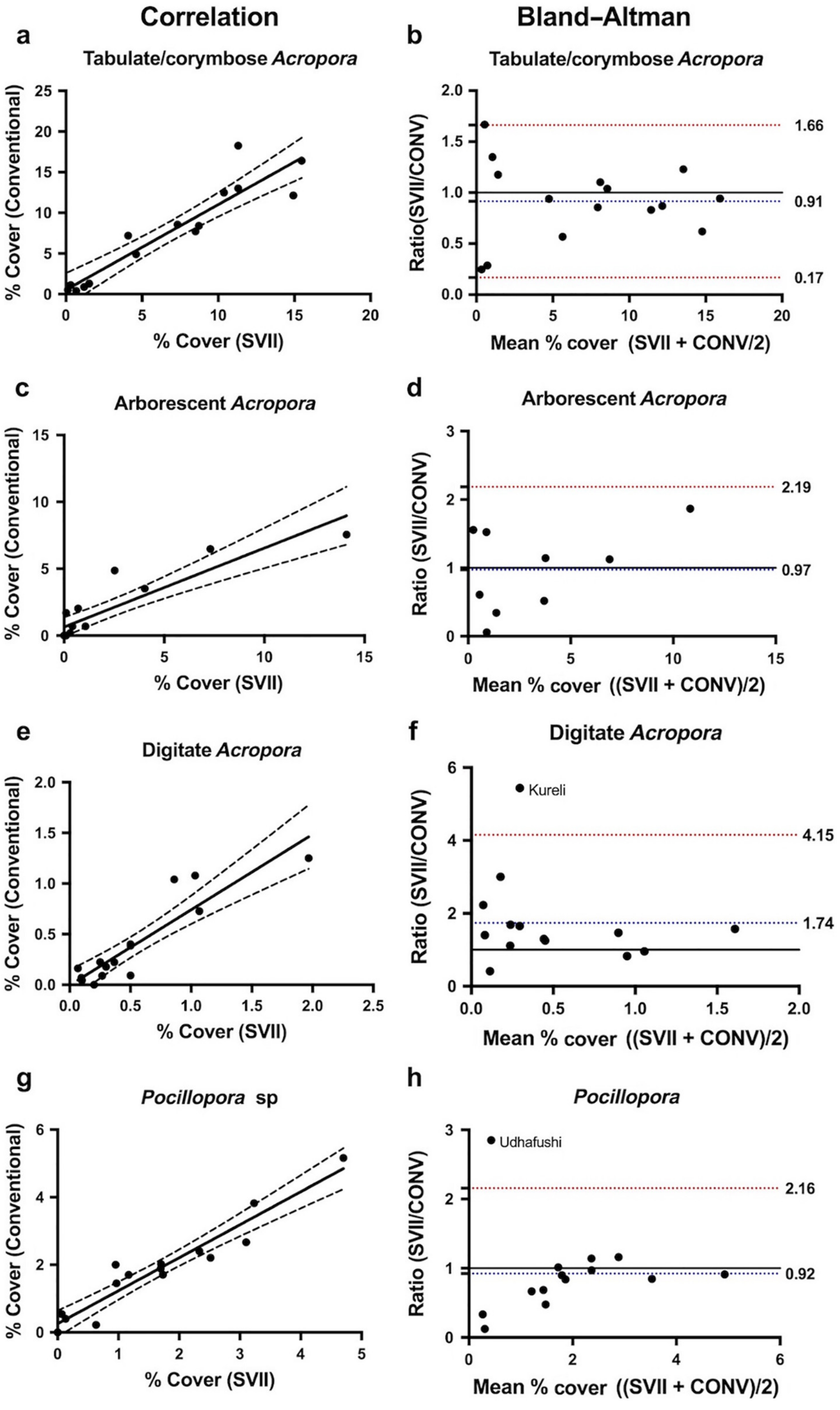

Fig. 6. Correlation (with 95% confidence bands) and Bland–Altman method agreement plots for percent cover of *Acropora* labels surveyed by SVII and conventional (CONV) methods across 50-m linear transects at 15 coral

(Fig. 6. *Continued*)
reef sites from the XL Catlin Seaview Survey Maldives expedition from the 29th of March until the 17th of April 2015. * Indicates Spearman's rank correlation performed for correlation coefficient. Red line indicates 95% limit agreements, and blue line represents ratio bias between SVII and conventional methods for Bland–Altman plots.

higher percent cover of DHC and a consistently lower percent cover of other invertebrates compared with conventional methods. This can be attributed to the difference in image resolution between images by SVII after post-processing (1031 × 1031 pixels) and the conventional photoquadrats (4608 × 3456 pixels). The lowered image resolution limits the annotator's ability to identify organisms, which are too small or have smaller distinguishing features such as individual and colonial tunicates, small encrusting sponges, and hydrozoa. Therefore, these organisms are often missed with lowered image resolution and labeled as one of the labels within the DHC functional group. Most likely DHC was covered by epilithic algae matrix (EAM), which is usually defined as a multispecific assemblage of up to 1 cm in height (Connell et al. 2014, Beijbom et al. 2015). Small invertebrates such as the solitary tunicate (*Didemnum molle*) are known to only take up a small amount of benthic cover on coral reefs (<3%). However, *D. molle* was seen to reach nearly 12% cover at one site in the Maldives following the 1998 coral bleaching event (McClanahan 2000). *Didemnum molle* can quickly colonize empty spaces after disturbances and have been found to be settled on settlement plates in the Maldives after just two months (Clark 2000).

The hard coral functional group

Overall, the two methods were in significant agreement when identifying the different types of coral within the label set (Table 2), emphasizing the ability of the SVII to assess coral community composition. The two methods recorded very similar amounts of overall percent hard coral. Agreement between the two methods improved to different extents when more defined labels were assessed (e.g., tabulate/corymbose *Acropora*, arborescent *Acropora*, massive *Porites*, massive small and invisible polyps, massive meandering, and TFP labels). The correlation and agreement within coral labels is an important result as the potential loss of major reef-building coral such as *Acropora* on coral reefs can lead to declines in spatial complexity and therefore eliminate habitat for many reef-dwelling organisms such as reef fish and invertebrates (Bellwood et al. 2004, Alvarez-Filip et al. 2009).

Image resolution may have influenced the ability of the annotator to pick out the definition of massive large round polyps (i.e., *Favia* sp., *Favites* sp., *Diploastrea heliopora*, *Goniopora* sp.). Therefore, massive corals with large round polyps may have been identified as massive corals with small or invisible polyps, further explaining why SVII estimated a higher percent cover of massive small/invisible polyp colonies over conventional methods. However, being able to differentiate between different types of massive corals can potentially provide greater insights into the diversity of coral within the community composition. The life history traits of many massive corals are thought to be similar (e.g., stress tolerant and slow growing) (Darling et al. 2012). Shifts in community assemblages toward more "stress-tolerant" and "weedy" (e.g., *Pocillopora* sp.) species have been observed after bleaching events and in areas with high fishing impacts (Darling et al. 2013).

Quantifying the coral community composition on coral reefs is extremely important and more valuable to management than knowing hard coral cover alone (Bellwood et al. 2004). Disturbance events can affect some coral morphologies more than others. Cyclones, for example, can often lead to a much greater reduction in branching *Acropora* than other massive or encrusting corals (Brown 1997). Furthermore, it is important to identify shifts in coral community composition through time, after major disturbance events, in order to explore the reef recovery process. Frequent disturbance events in Moorea, French Polynesia, between 1979 and 2003 caused taxonomic shifts in coral composition from tabulate *Acropora*- and *Montipora*-dominated reefs to reefs with a relative abundance of *Pocillopora* and massive *Porites* (Pratchett et al. 2011).

The Maldives went through an extreme underwater heatwave in April 2016, which leads to the mass die-off of reef-building corals and COTS (*Ancanthaster planci*) in some sites, which drove a major decline in *Acropora* at

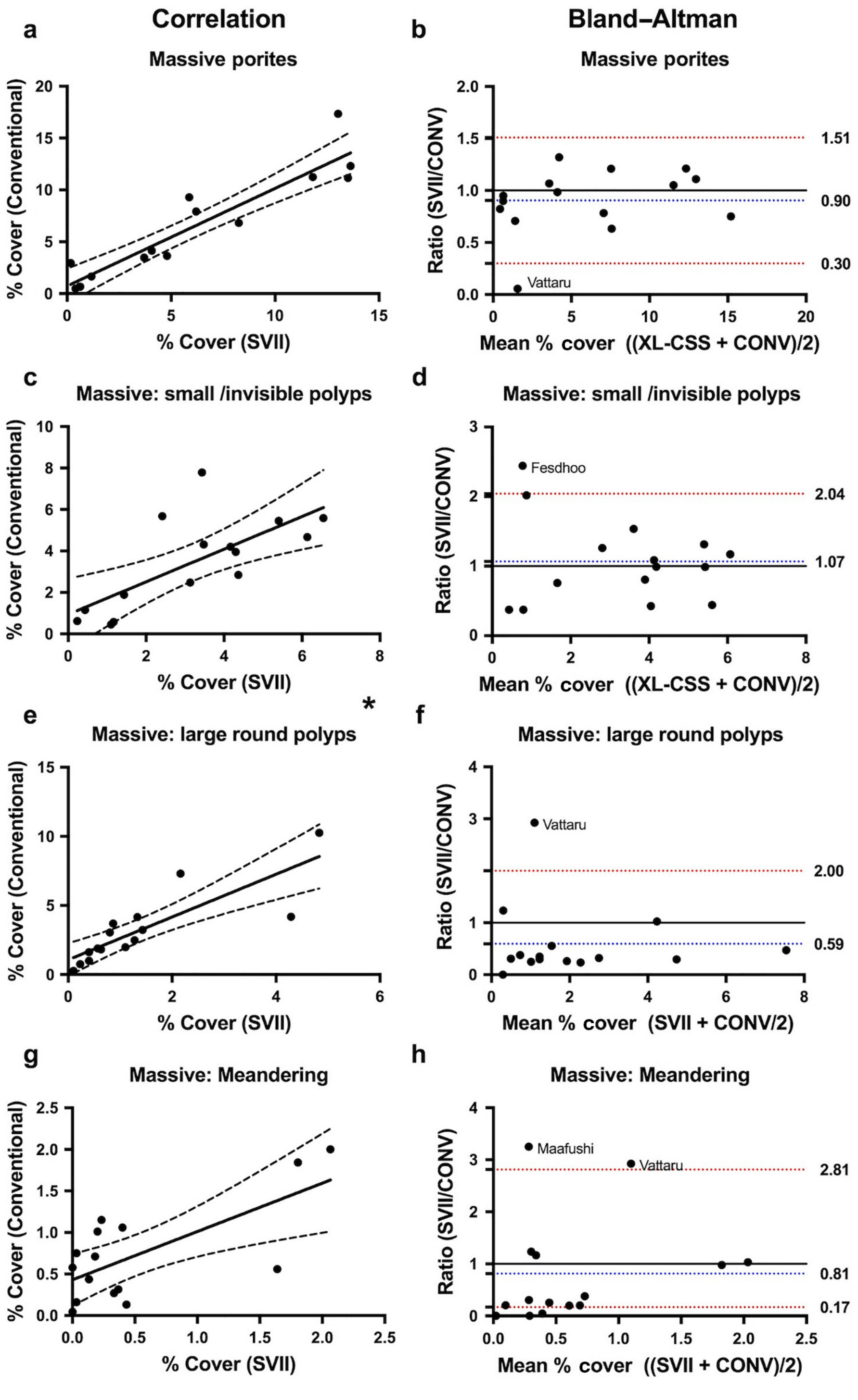

Fig. 7. Correlation (with 95% confidence bands) and Bland–Altman method agreement plots for percent cover of massive coral labels surveyed by SVII and conventional (CONV) methods across 50-m linear transects at 15 coral reef sites from the XL Catlin Seaview Survey Maldives expedition from the 29th of March until the 17th of April 2015. * Indicates Spearman's rank correlation performed for correlation coefficient. Red line indicates 95% limit agreements, and blue line represents ratio bias between SVII and conventional methods for Bland–Altman plots.

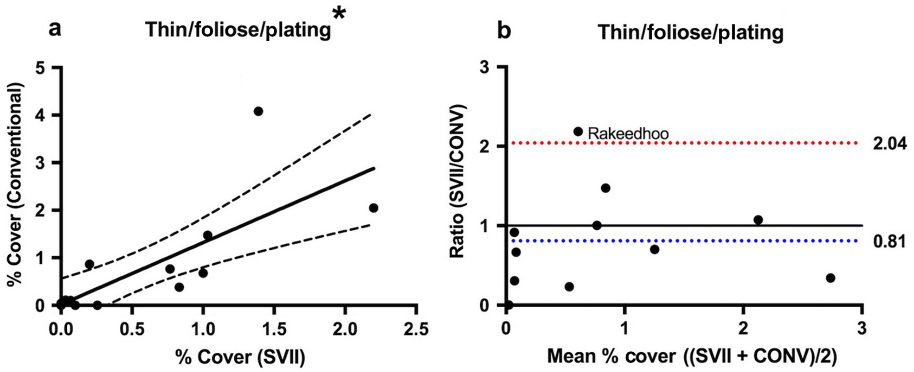

Fig. 8. Correlation (with 95% confidence bands) and Bland–Altman method agreement plots for percent cover of thin/foliose/plating corals surveyed by SVII and conventional (CONV) methods across 50-m linear transects at 15 coral reef sites from the XL Catlin Seaview Survey Maldives expedition from the 29th of March until the 17th of April 2015. * Indicates Spearman's rank correlation performed for correlation coefficient. Red line indicates 95% limit agreements, and blue line represents ratio bias between SVII and conventional methods for Bland–Altman plots.

various sites in 2015 (Pisapia et al. 2016). Being able to detect a change in coral composition at larger scales on coral reefs will provide valuable information in terms of initial mortality and recovery from both the coral bleaching event and *A. planci* outbreaks.

Other invertebrates

There was significant correlation and relative agreement between the two methods when identifying soft corals (*Alcyonaceans*). This is important to know because soft corals in the family *Alcyonacea* are a major sessile invertebrate on Indo-Pacific reefs, often dominating disturbed reefs when they are present (Dai 1991). However, they can also be affected by disturbances such as bleaching events (Wilkinson 1999). Also, *D. molle* (solitary tunicate) estimations were correlated between methods, but were consistently showing a higher percent cover in the conventional photoquadrats. As mentioned above, this is most probably due to image resolution making it difficult to identify small solitary tunicates (<2 cm) that are not dominating to compositions of the reef. Massive encrusting sponges were not correlated between methods. This is most likely due to image resolution and rarity of encrusting sponges found at the sites visited in the Maldives during the 2015 XL CSS expedition, or the cryptic nature of encrusting species in general. Encrusting sponges have key roles on coral reefs such as bio-erosion and competition for space (Diaz and Rützler 2001, Bell 2008, González-Rivero et al. 2013). Detecting changes in rare or exotic species requires different survey techniques than the two used for this study, such as those used to detect marine bioinvasions (Campbell et al. 2007).

CONCLUSIONS

Our results demonstrate that the SVII provides an important tool for rapidly, accurately, and rigorously surveying coral reefs at multi-kilometer scales while maintaining taxonomic resolution that is comparable to conventional methods at much greater scales. The larger spatial scale (1.5–2 km per dive) that the SVII was able to achieve provides an important bridge to remote sensing techniques (Mumby et al. 2004, Roelfsema and Phinn 2010, Phinn et al. 2012). Furthermore, the scale provided by SVII also provides a link with satellite imagery that is used to measure and relate biophysical parameters (e.g., sea surface temperature (SST), chlorophyll-*a*, wind/wave exposure, and light attenuation) to the spatial patterns observed using the SVII (Mumby et al. 2011, Chollett and Mumby 2012, Yamano 2013, González-Rivero et al. 2016). These linkages are likely to become of increasing importance as large-scale changes to the environment from climate change impact reefs more and more. This type of information will be critical as the scientific

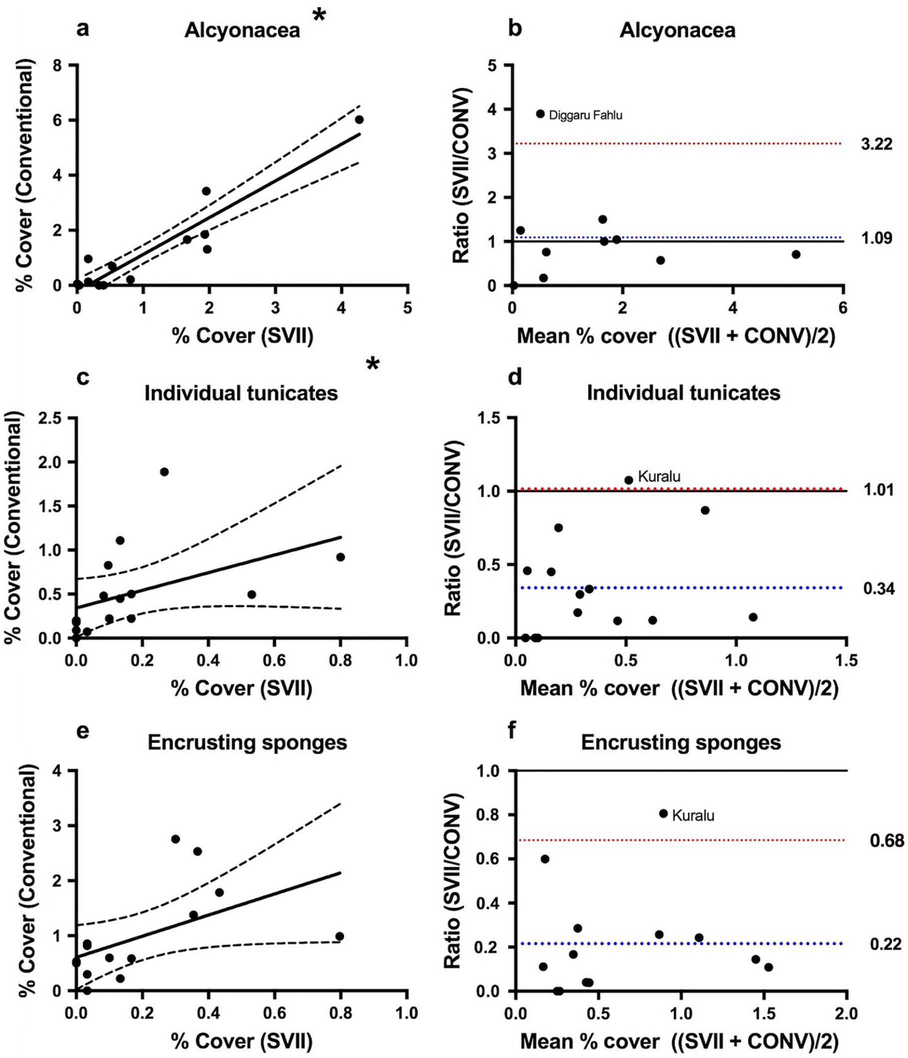

Fig. 9. Correlation (with 95% confidence bands) and Bland–Altman method agreement plots for percent cover of other invertebrates surveyed by SVII and conventional methods across 50-m linear transects at 15 coral reef sites from the XL Catlin Seaview Survey Maldives expedition from the 29th of March until the 17th of April 2015. *Indicates Spearman's rank correlation performed for correlation coefficient. Red line indicates 95% limit agreements, and blue line represents ratio bias between SVII and conventional methods for Bland–Altman plots.

and management communities seek to understand the resilience of coral reefs in a changing world. In the latter case, technologies such as the SVII are likely to offer the ability to rapidly detect more robust (or indeed, less robust) sections of coral reefs for conservation action. Technologies such as the SVII have the potential for providing a global series of baseline measurements estimating the state of coral reefs, which is essential for understanding how coral reefs are likely to change over the coming decade and century.

ACKNOWLEDGMENTS

This study was undertaken as part of the XL Catlin Seaview Survey, designed and undertaken by the Global Change Institute, and funded by XL Catlin Pty Ltd in partnership with The Ocean Agency and The University of Queensland. DEPB was supported by The Australian Government Research Training Program Scholarship through The University of Queensland, and OHG was supported by an ARC Laureate Fellowship. The SVII camera system was invented by Richard Ververs, Aaron Spence, and Christophe

Bailhache. The authors would like to also acknowledge the XL Catlin Seaview Survey project management and field team at the Global Change Institute for their tireless efforts in arranging all associated field activities, and also acknowledge the technical assistance with image processing from Panedia. We would also like to thank the Maldives government and members of the Marine Research Centre, Ministry of Fisheries and Agriculture, and Environmental Protection Agency for their assistance with permitting and in-country knowledge. Finally, we would like to recognize the excellent efforts of boat crew and administration team from MV Emperor Voyager for proving an excellent research vessel with no delays occurring during our expedition.

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