



OPINION PIECE

Mesophotic coral reef community structure: the constraints of imagery collected by unmanned vehicles

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ABSTRACT: There is a critical need to quantify and monitor mesophotic coral reef community structure and function at multiple spatial and temporal scales. Because accessing these habitats is costly in terms of infrastructure and effort, often for a modest return in data, many investigators collect digital imagery using transect techniques from unmanned platforms. Specifically, remotely operated vehicles and autonomous underwater vehicles are used because they operate at deeper depths for extensive periods of time, can carry an array of oceanographic and imaging instruments, and can collect and archive extensive amounts of video and still imagery. However, substrate angle, camera angle, and vehicle position above the benthos creates varying degrees of error in the imagery due to parallax and geometric distortion. Photogrammetry conducted on 2D photographs from uncorrected 3D imagery can over- or under-estimate the percent cover, biomass estimates, and abundance of the benthic groups of interest. Here we illustrate these errors and emphasize the requirement for post-processing of imagery to ensure that these data can be used for valid quantitative ecological descriptions of mesophotic benthic communities in the future.

KEY WORDS: Photogrammetry · Mesophotic · Remotely operated vehicle · ROV · Autonomous underwater vehicle · AUV · Parallax · Image distortion · Sponges

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1. INTRODUCTION

A cornerstone of ecological research is quantifying the abundance and percent cover of multiple biological units over varying temporal and spatial scales. On coral reef ecosystems, these data allow an assessment of biodiversity, changes in community structure, species turnover, and potential to understand functional differences between coral reefs. The best methodology for quantifying these metrics on coral reefs has been under discussion since the 1960s and

1970s (Loya 1978) and continues today (Jokiel et al. 2015). Most researchers currently use diver-operated digital still and video cameras mounted in frames (e.g. quadropod, Fig. 1a) with a fixed focal distance that is oriented perpendicular to the substrate. This allows for the acquisition of vertically oriented (i.e. nadir) images with scale for the analysis of photographs, and quantification of various metrics (i.e. photogrammetry) associated with ecological community structure (Williams et al. 2019). This approach is common in shallow (<30 m) coral reef habitats where

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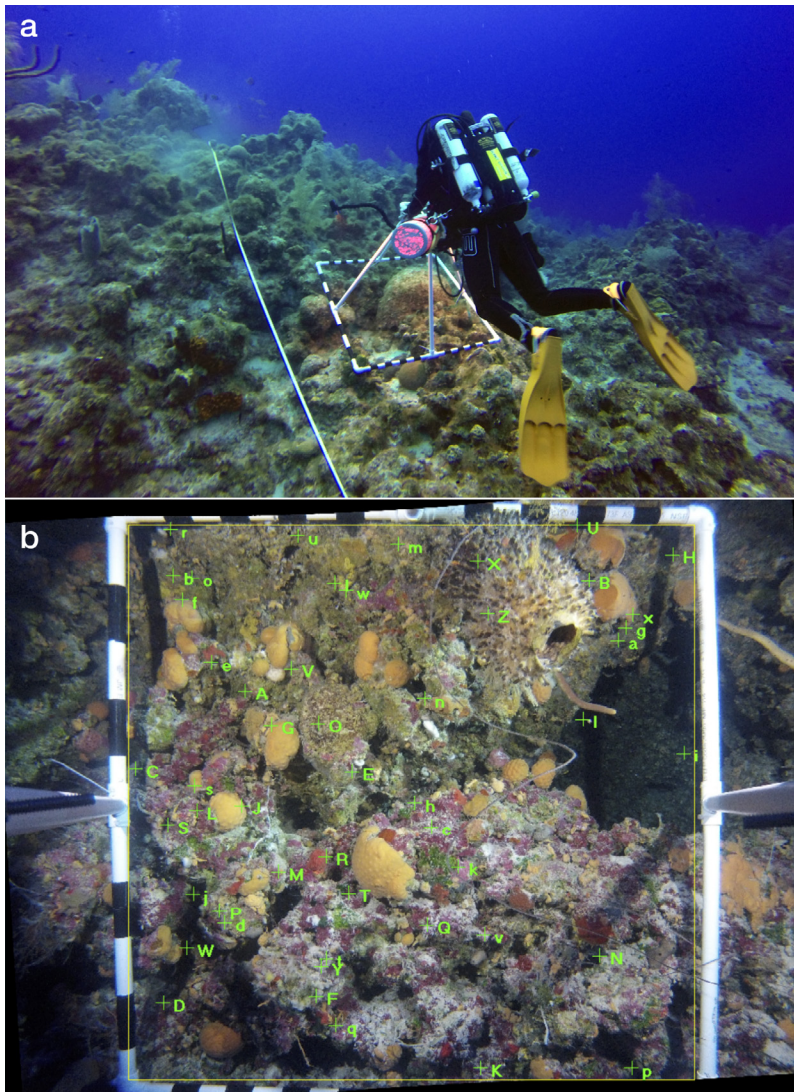


Fig. 1. (a) Diver using a 'quadropod' photographic frame with camera (GoPro Hero 2) and auxiliary lighting (SOLA Video) perpendicular to the substrate at a fixed focal distance. Photograph by Elizabeth Kintzing. (b) Typical image from a quadropod taken at 91–92 m on Grand Cayman. The only correction required for these photographs was for refraction error using PT Lens (v. 9.2), and the random point overlay (green symbols and letters) was generated by CPCe (v. 4.1). Note the abundance of demosponges and sclerosponges at this depth. Photograph by Keir Macartney

it largely avoids, and is able to easily correct for, many of the errors associated with varying topography (Fig. 1a).

Unfortunately, shallow coral reef biodiversity is predicted to decline in the future due to multiple factors associated with increases in world population and climate change (Hoegh-Guldberg et al. 2017). One result of this has been increased interest in mesophotic coral ecosystems (MCEs: 30–150 m, Lesser et al. 2018) since these have been estimated to represent

~80% of the areal coverage of the world's coral reefs (Pyle & Copus 2019). Given the growth of MCE research in the last decade (Loya et al. 2016), there is a clear need to accurately acquire, and analyze, basic quantitative information on the community structure of MCEs on spatial and temporal scales that match the areal extent of these habitats. While diver-based assessments of community structure using transects and quadrats, including photoquadrats (Fig. 1), have provided some baseline data on MCEs (Slattery & Lesser 2012, Macartney et al. 2020), the acquisition of imagery using remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) equipped with digital video and still cameras has increased significantly in recent years, and will continue to increase to meet the demand for quantitative ecological descriptions of MCEs over broad spatial and temporal scales (Armstrong et al. 2019).

In contrast to diver-based collection of imagery, both ROVs and AUVs, even when they are capable of maintaining a fixed height from the substratum, are faced with significant variation in topographical relief, and therefore substrate angle variability on MCEs (Locker et al. 2010). This makes the ability to maintain a camera perpendicular to the substratum difficult at best. When water currents from multiple sources are factored into the equation, vehicle buffeting in 3 dimensions can further complicate the angle of image capture. The associated changes in topographical relief and/or inability to maintain the camera per-

pendicular to the substrate introduce both parallax error and geometric distortion. Parallax displaces the isocenter of the image, causing scaling errors, while geometric distortion changes the areal surface area of the image captured as well as the size of objects in the image and final photographs used for analysis. The magnitude of these effects is determined by the severity of the oblique angle of view of the image. These are not new phenomena and they have been considered previously in shallow coral reef studies

that use quantitative imagery (e.g. Done 1981). In addition, they have been a focus of image quality control for decades in the airborne remote sensing community, where oblique imagery is routinely used for both applied and basic objectives (e.g. Morgan et al. 2010, Colomina & Molina 2014). The use of remotely sensed imagery for photogrammetry requires both pre-planning and post-processing (Morgan et al. 2010), as does the imagery from habitats with highly varying topography such as MCEs (Lesser et al. 2018). Both vehicle and camera tilt, as well as substrate angle, should be recognized as *a priori* sources of error and accounted for during post-processing prior to any quantitative analysis of data from ROVs and AUVs (Wakefield & Genin 1987, Tusting & Davis 1993). The goal of imagery post-processing is to obtain orthorectified photos showing the habitat in detail with true distances, angles, and areas without distortion, and with a single scale throughout the image.

2. CASE STUDIES FOR MESOPHOTIC CORAL REEFS

Because of the effects of climate change, shallow coral reef community structure has undergone a number of ecological 'phase shifts,' and sponges have been predicted to become 'winners' on shallow coral reefs of the future (Bell et al. 2018; but see Lesser & Slattery 2020 for an alternative view). Nevertheless, sponges increase in abundance with increasing depth on many coral reefs, especially in the Caribbean Basin (e.g. Jamaica, Bahamas, Cayman Islands), due to the increasing availability of food (Lesser & Slattery 2018, 2019, Lesser et al. 2018, 2019). Specifically, autotrophic corals and macroalgae decrease in abundance with increasing depth into the mesophotic zone due to light limitation, and these functional groups are replaced by increasing sponge cover, biomass, and biodiversity due to their ability to feed on both particulate and dissolved organic material (Slattery & Lesser 2012, Lesser et al. 2018). Experimental studies have demonstrated the important role of food availability on sponge populations (e.g. Trussell et al. 2006), while both abiotic and biotic effects on sponge population dynamics results in reef-to-reef variability that influences the distribution and abundance of sponges (e.g. Wulff 2017, Lesser et al. 2018, Pomponi et al. 2019).

Multiple studies examining MCE habitats using imagery from AUV/ROVs show both scalar errors and geometric distortion of images and/or describe very little, or no, post-processing of oblique imagery

(Singh et al. 2004, Armstrong et al. 2006, Rivero-Calle et al. 2009, Locker et al. 2010, Armstrong & Singh 2012, Etnoyer et al. 2016, Pyle et al. 2016, Silva & MacDonald 2017, Scott et al. 2019). Similarly, data from MCEs in Puerto Rico, St. Thomas (USVI), and the Flower Garden Banks, using imagery collected by both AUVs and ROVs, indicated that sponges either decrease, or do not change, in percent cover with increasing depth (Pawlik & Scott 2019, Scott et al. 2019). Pawlik & Scott (2019) used the data from Rivero Calle (2010), which overlapped at one site (Isla Desecheo) in Puerto Rico with data collected using diver-deployed permanent transects, as well as quantification of the benthic communities using intercept chain-link and digital video approaches (Garcia-Sais 2010). However, Garcia-Sais (2010) reported a pattern of increasing sponge cover with depth. The differences in the trajectory of these sponge populations with depth could be the result of between-reef variability within a site. Looking at the percent cover of sponges as a function of depth using these 2 approaches shows that in Garcia-Sais (2010), sponge cover varied between ~2 and 30% from 15 to 50 m, while sponge cover from Rivero Calle (2010), used in the study by Pawlik & Scott (2019), varied between ~2 and 16% from 30 to 100 m.

Given the similarity in the percent cover in these data, we decided to look at the quality control and post-processing of the ROV/AUV imagery as potential sources of error relative to the long-time standard of diver-based transects and quadrats/photoquadrats (Fig. 1). Pawlik & Scott (2019) used the benthic data from Rivero Calle (2010), derived from AUV imagery, collected on both 'steep' and 'gradual' slopes. Rivero Calle (2010) reported that the camera distance to the seabed was kept constant, which created photoquadrats of 4 m². There is no description, however, of any post-processing of the imagery required to correct for parallax-related scaling errors and geometric distortion of the imagery over the varying substrate angles (Fig. 2). Scott et al. (2019) analyzed ROV imagery acquired by the NOAA Undersea Vehicle Program at the University of North Carolina at Wilmington, where no post-processing is provided to the end user (J. White pers. comm.), from Puerto Rico, St. Thomas, and the Flower Garden Banks. Again, no description of imagery post-processing by the investigators was provided for these locations known to have varying topography and substrate angles. Both Scott et al. (2019) and Pawlik & McMurray (2020) stated that AUV and ROV imagery does not require any post-processing because the use of randomized points on a photo-

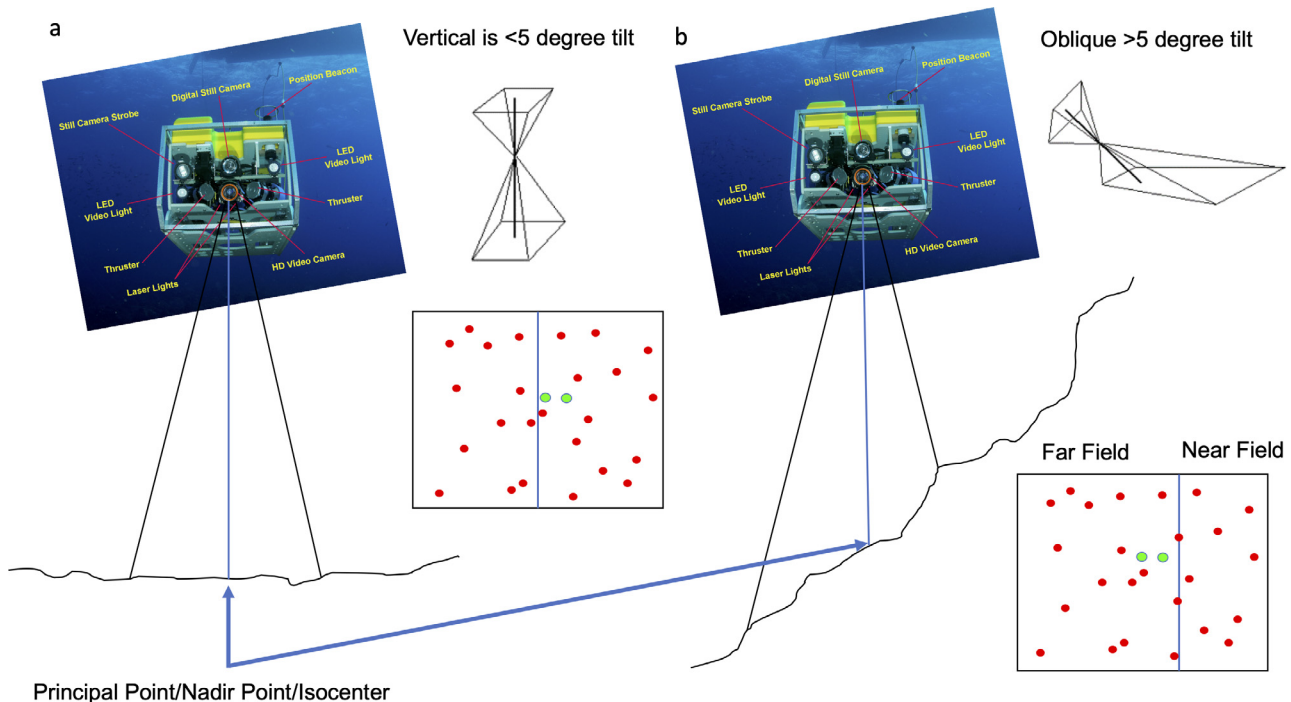


Fig. 2. (a) Remotely operated vehicle (ROV) collecting imagery from a vertically oriented camera perpendicular to a flat substrate. The principal point, nadir point, and isocenter all converge in the center of the image taken by the camera. Laser reference scaling points are illustrated as green dots, and a random point density distribution is seen in the image (~50 % of the random points are on each side of the isocenter). (b) ROV collecting imagery from a vertically oriented camera perpendicular to an oblique substrate. The principal point, nadir point and isocenter still converge in the center of what is now a trapezoidal 3D image captured in a 2D format. This creates a far field and near field in the photograph and a displaced image isocenter where point density is not randomly distributed throughout the photograph (~33 % of the random points are on the nearfield side of the isocenter). ROV photo credit from NOAA Flower Garden Bank National Marine Sanctuary by G. P. Schmahl

graph to estimate percent cover is not subject to parallax error. They further stated that any differences in the total area of the photograph caused by changes in the angle of the substratum and subsequent geometric distortion would have no effect on the random distribution of the points projected on an image for the purposes of calculating the percent cover of different benthic taxa. These assumptions are incorrect (see Section 3), and the apparent absence of post-processing of the AUV and ROV imagery means that the final photographs used for the quantitative analysis of community structure with depth were not orthorectified and therefore introduced varying amounts of preventable error. While ROVs and AUVs operate at deeper depths for longer time periods than technical divers, and can collect more imagery data, the advantages of AUVs and ROVs to characterize MCEs can only be realized if the collected imagery undergoes appropriate post-processing to remove as many sources of error as possible, and thus increase the accuracy of the ecological descriptions of benthic communities (Lirman et al. 2007, Bryson et al. 2017).

3. WHERE ARE THE ERRORS IN UNDERWATER IMAGERY?

Most cameras were designed for use in air and, even with a dome port, optical effects related to the air–sea interface (i.e. refraction) when used underwater can result in erroneous areal estimates due to the changes in angular field of view. The field of view for a camera is calculated using the focal length and the format size of the image sensor (Tusting & Davis 1993, Heikkila & Silven 1997, Shortis et al. 2009). Corrections for these camera effects in images must be undertaken in order to accurately quantify the size of an image (Tusting & Davis 1993, Kunz & Singh 2008). Additionally, an image taken at a known distance in a vertical orientation, where the pitch, roll, and yaw of the vehicle is eliminated as much as possible, results in images with $<5^\circ$ variation in tilt and subsequently less than 0.5% error in the determination of areal coverage of the image (Scherz 1974). This results in a photograph that is functionally perpendicular, and where the principal point, nadir point, and isocenter of the

photograph all converge (Fig. 2a). This also ensures that any reference scaling lasers in the imagery (e.g. green dots in Fig. 2a) represent the same scale over the entire image because the distance between the substrate and the camera is approximately the same throughout the image. Thus, any overlay of a grid or random points will be evenly distributed within the image, resulting in low inherent errors associated with any calculations (i.e. percent cover) conducted (e.g. Fig. 1b).

When the orientation of the image is $>5^\circ$ variation in tilt, it is considered an oblique angle image (Shufelt 2000). Using the perpendicular image as a reference point (Fig. 2a), any oblique image of the same area caused by a change in camera angle, or an image where the substrate slope varies (Fig. 2b), is subject to parallax error and geometric distortion of the image. Both parallax error, an apparent change in the relative position of fixed objects (i.e. nadir point of image), and geometric distortion introduce errors proportional to the oblique angle of the image. Because of this, oblique images are actually trapezoidal in shape (Tusting & Davis 1993), rather than rectangular and encompass greater total area than an image taken perpendicular to the substrate (Fig. 2b). Scaling effects will also occur in oblique images as a result of varying distances from the camera to the substrate throughout the image (Wakefield & Genin 1987, Tusting & Davis 1993, Dias et al. 2015). For example, in Fig. 2a, an ROV is shown conducting a video transect on a flat substrate at a fixed altitude. Here, errors associated with parallax and scaling are minimized significantly, or are absent (e.g. Slattery et al. 2018). Fig. 2b shows the same ROV running parallel to a sloping reef while the camera is still oriented vertically to the substrate. However, the ROV is no longer perpendicular to the substrate such that the image in Fig. 2b is oblique; this results in a trapezoidal shape with larger areal coverage than the image depicted in Fig. 2a. This 3D trapezoidal area is captured by the 2D format of the camera sensor as rectangular, and the areal coverage is actually larger than the image in Fig. 2a but is not visually apparent. All calculations of abundance based on this larger area would be incorrect because the assumed area of the image, or any overlaid quadrat in the image (sensu Scott et al. 2019), to normalize the imagery is smaller than the actual area, causing inflated estimates of abundance, percent cover, and/or biomass. In regard to quadrats overlaid onto imagery, the reference points used for scale (i.e. lasers: depicted in Fig. 2b as green dots) provide

scale only for the line parallel to the isocenter of the image. Using this scale in any other portion of the image would result in incorrect measurements of a superimposed quadrat, or the size and volume for any taxon.

In addition, because the image isocenter in Fig. 2b is displaced (i.e. parallax error) in the final rectangular photograph, it creates a far field (i.e. downslope) and near field (i.e. upslope) appearance, each representing 50% of the image area as captured by the camera (Fig. 2). Any random point overlay of this image will result in an uneven distribution of points from which to calculate percent cover, or any other metric, and will introduce additional systemic errors into the estimated abundances of various taxa. For example, the point density in the image in Fig. 2b is not randomly distributed, as only 32% of the 25 points ($n = 8$ points) are located in the near field that represents 50% of the photograph compared to 17 points in the far field. Combined with the larger area used to normalize abundance, the skewed distribution of the point density will affect both mean and variance estimates of abundance or percent cover. Additionally, using the equations in Scherz (1974), a 30° tilt in camera angle (i.e. an oblique image) will cause a 21% error in the measurements of linear distance. Because of the unaccounted scaling effects and geometric distortion in these images, the results (i.e. mean $\pm$ SD) calculated have significant amounts of unaccounted error. This error will also affect the quantification of different taxa at different depths as abundance changes, for example, assume a 20% error in percent cover estimates from imagery due to scaling effects and geometric distortion. At 91 m on the reefs of Grand Cayman, the percent cover of the sponge *Plakortis angulospiculatus* is 12.03 ± 3.35 per m^2 , while *Agelas tubulata* is 0.38 ± 0.19 per m^2 (Macartney et al. 2020). Assuming a 20% error in the mean $\pm$ SE percent cover estimate for *P. angulospiculatus* could result in values as high as 14.44 ± 4.02 per m^2 and 0.46 ± 0.23 per m^2 for *A. tubulata*. In absolute terms, the error for the 'true' mean of *A. tubulata* does not even result in percent cover estimates for this species $>1.0\%$ cover, while the deviation from the true mean percent cover for *P. angulospiculatus* with 20% error is already substantial and significant (ANOVA: $F_{1,59} = 6.15$, $p = 0.016$). Thus, imagery collected by these vehicles, in the absence of post-processing, should only be used for qualitative descriptions, or presence/absence studies (e.g. Englebert et al. 2017).

4. GENERAL CONSIDERATIONS FOR IMAGE COLLECTION, POST-PROCESSING, AND PHOTOGRAMMETRY

We suggest that the collection of imagery in habitats with varying topography should start with a detailed discussion with the pilots of AUVs/ROVs (i.e. pre-planning). Qualitative surveys guided by local charts of the sites should be considered to identify topography for eventual quantification (i.e. geo-referenced acoustic bathymetry, laser line scanning, or side scan sonar), along with qualitative imaging to ascertain relative community abundances and appropriate scale for which quantitative techniques could be applied. Survey planning can also include the collection of data on abiotic conditions that might be relevant to the habitat (e.g. irradiance, temperature, and water flow as a function of depth), and the collection scheme (i.e. size of sampling units) and number of cameras (i.e. for the pilot and the scientist). These data should also define the number of independent images required for comparative statistics across the depth gradient of the study site (Durden et al. 2016). The most important mission planning component is determining the camera angle to be used, and altitude and tilt of the ROV from the preliminary surveys. For many Caribbean sites, it may actually be more practical to conduct any shallow water transects with varying substrate slopes by diver, while deeper (>30–50 m) depths where the vertical wall begins to develop can be done using an ROV/AUV oriented perpendicular to the wall (*sensu* Reed et al. 2018).

From an imagery acquisition perspective, a single high-definition still image camera with a fixed focal length is the best choice for quantitative purposes, in addition to artificial illumination. The camera should be oriented perpendicular to the substrate at a fixed distance by maintaining a constant vehicle altitude, and the camera should be corrected for refraction error as needed. In this case, scaling lasers can be used throughout the image, and quantification can proceed with little additional imagery correction. When that is not possible, oblique images can be quantified using extensive ground truthing and a 2-laser system (Dias et al. 2015), or using a 4-laser system (e.g. Tusting & Davis 1993), which would allow the camera to be tilted in both the vertical and horizontal directions to obtain all measurements required for the calculation of the actual area of the image and scale anywhere on the image (see Spaulding et al. 2003 for a successful application on temperate mesophotic reefs to quantify benthic macroalgae

using an ROV). Alternatively, the construction of a perspective ('Canadian') grid (*sensu* Wakefield & Genin 1987), which can result in accurate and quantitative ecological information from the image, could be carried out. The construction and use of a Canadian grid on oblique imagery can identify those areas of the image (i.e. near field) where the most accurate measurements can be made, which decreases as sampling moves further away from the nadir point (Wakefield & Genin 1987). Another approach is to use dual video cameras to get stereo images that provide accurate and reliable 3-dimensional (3D) data. Subsequently, using analytical approaches, such as structure from motion, will provide surface topography that is extremely accurate (Shortis et al. 2008, Bryson et al. 2017). Stereo video imagery can also be used to accurately calculate the area of an image and provide scale throughout the image so quadrats are not needed, and the footage can also be used to create 3D models of reef complexity, surface area, and biomass, as well as quantitative community structure (Burns et al. 2015, Price et al. 2019). Lastly, software packages are available, such as Laser Measure™ and Optimas™, that can be integrated with data collected using the 4-laser system discussed above, or to construct and overlay a perspective grid on oblique imagery for accurate photogrammetry (Barker et al. 2001).

5. CONCLUSIONS

Quantifying changes in sponge communities spatially and temporally on shallow and mesophotic reefs is essential to contextualize their response(s) to climate change, their roles in benthic–pelagic coupling, and sponge-mediated biogeochemistry of nutrients on coral reefs (de Goeij et al. 2017). Additionally, accurate information on coral reef community structure is essential to understand the ecological processes (i.e. top-down versus bottom-up effects) that regulate sponge populations, and their interactions with other members of the coral reef community (Wulff 2017), on both shallow and mesophotic coral reefs (Lesser & Slattery 2013, Slattery & Lesser 2015).

As in any scientific endeavor, the central issue is, 'What is the question?' If quantitative imagery is desired, then there is an implicit requirement to minimize as many sources of error as possible in the collection, post-processing, and analysis of imagery; and this is especially true for imagery collected from ROVs and AUVs. Minimizing error will require describing the quantification of image size, as well as

accounting for all sources of image distortion and scaling errors as described above. Where these errors occur, the post-processing steps employed to remove, or minimize as much as possible, these sources of error (i.e. to obtain orthorectified images), should be described in detail, and is required prior to the overlaying of any grid of random points for point-count analyses, which itself should include an analysis of point density versus percent cover (Pante & Dustan 2012). The lack of imagery post-processing will result in the introduction of errors which will propagate throughout the analysis of imagery, decrease the accuracy of estimates of percent cover, abundance, and biomass of coral reef taxa, and misrepresent the ecological structure of mesophotic coral reef communities spatially and temporarily.

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