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Methods and measurement variance for field estimations of coral colony planar area using underwater photographs and semi-automated image segmentation

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Abstract Size and growth rates for individual colonies are some of the most essential descriptive parameters for understanding coral communities, which are currently experiencing worldwide declines in health and extent. Accurately measuring coral colony size and changes over multiple years can reveal demographic, growth, or mortality patterns often not apparent from short-term observations and can expose environmental stress responses that may take years to manifest. Describing community size structure can reveal population dynamics patterns, such as periods of failed recruitment or patterns of colony fission, which have implications for the future sustainability of these ecosystems. However, rapidly and non-invasively measuring coral colony sizes in situ remains a difficult task, as three-dimensional underwater digital reconstruction methods are currently not practical for large numbers of colonies. Two-dimensional (2D) planar area measurements from projection of underwater photographs are a practical size proxy, although this method presents operational difficulties in obtaining well-controlled photographs in the highly rugose environment of the coral reef, and requires extensive time for image processing. Here, we present and test the measurement variance for a method of making rapid planar area estimates of small to medium-sized coral colonies using a lightweight monopod image-framing system and a custom semi-automated image segmentation analysis program. This method demonstrated a coefficient of variation of 2.26 % for repeated measurements in realistic ocean conditions, a level of error appropriate for rapid, inexpensive field studies of coral size structure, inferring change in colony size over time, or measuring bleaching or disease extent of large numbers of individual colonies.

Keywords Coral reefs · Colony size · Colony growth · Size structure · Planar area · Image segmentation

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Introduction

Coral reef ecosystems are in decline worldwide (Knowlton and Jackson 2008; Pandolfi et al. 2003;

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Hoegh-Guldberg et al. 2007). These ecosystems support fisheries producing essential protein and export products for many nations, provide protection for often highly populated shorelines, enable economic opportunities from tourism, and are repositories of biodiversity that in many cases has not yet been fully described. Despite this recognized importance, worldwide degradation of coral reef ecosystems is increasing in many locations.

Accurately measuring individual coral colony sizes in situ contributes to advancing our understanding of these changes in coral ecosystems. Specifically, individual coral colony measurements can provide information for describing community size structure and population and growth dynamics on coral reefs (Bak and Meesters 1998) and for determining the impacts of various environmental disturbances (Edmunds and Elahi 2007). Population size structure and individual colony size change trajectories (i.e., from growth, mortality, partial mortality, or fragmentation) have also been shown be closely related to a number of influential environmental conditions, including water temperature (Barott et al. 2009), organic carbon concentrations (Cohen and Holcomb 2009), and nitrogen load (Pandolfi et al. 2003). Evaluating the effects of these environmental and water quality variables on community size structure or growth of corals in areas affected by these conditions is dependent on obtaining accurate measurement of individual colony sizes and tracking changes in colony sizes over time.

However, obtaining non-invasive, accurate, and replicable in situ measurements of individual coral colony size can be surprisingly difficult. Furthermore, there is also a need for simple, low-cost methods, as many of the countries with the greatest coral resources, and hence the most affected by the global decline of these ecosystems, are countries with limited public, academic, and non-profit resources that can be directed towards coral science or reef ecosystem monitoring (Cesar et al. 2003).

Field methods for assessing coral colony size (using a variety of metrics, not necessarily directly comparable) currently include making visual estimates, binned into categories (Hughes 1984); measuring planar area from photographs obtained using support hardware that is attached to the substrate (Rahav et al. 1991); taking hand measurements of the longest axis of each colony (Miller et al. 2000); using calipers to measure linear extension over time (Bongiorni et al. 2003); measuring planar area from photographs taken with a rigid rectangular or circular framer placed on the substrate (Edmunds and Elahi 2007); representing three-dimensional (3D) mass through extrapolation of multiple two-dimensional (2D) measurements (Holmes 2008); and estimating 3D surface area from photogrammetric techniques (Jones et al. 2008). There are varying disadvantages associated with each technique (Hill and Wilkinson 2004). Fixed points for attaching camera support hardware are not allowed in many research-only or protected areas, hand measurements are subject to operator and notation error, and the uni-dimensional measurements obtained cannot be well correlated with either two- or three-dimensional metrics and do not allow for later re-measurement or confirmation (Leujak and Ormond 2007). Framers can be large and difficult to use in highly rugose terrain (Bythell et al. 2001) and usually have the length reference fixed on the lower frame and cannot be adjusted to place this reference at appropriate colony height (usually the plane of greatest areal extent). Finally, 3D image sets require multiple photos and are laborious to obtain and process (Jones et al. 2008). Given these issues, there remains a need for simple, replicable, non-invasive, in situ coral colony size measurements requiring a minimum of equipment, which can be used for accurate and cost-effective coral ecosystem monitoring in a variety of situations and by groups with varying resources (Hill and Wilkinson 2004).

In addition to the field methods listed above, there are a variety of methods for determining coral colony size that involve impacting the colony through contact or destruction. These include determining surface area by covering with aluminum foil (Marsh 1970) or wax coating (Stimson and Kinzie 1991), surface area determination through spectrophotometer readings of dye coated samples (Ove Hoegh-Guldberg 1988), measuring displacement of buoyant weight in water (Spencer Davies 1989), measuring calcification rates through extractive coring and X-ray or CT scan analysis of the cores (De'ath et al. 2009), and deriving surface area from computer tomography (CT) scans (Laforsch et al. 2008; Naumann et al. 2009). These techniques requiring the colony to be removed from the environment and handled generally result in greater accuracy than those that can be performed in situ, but at significant cost of execution. A recent methods review for estimations of true surface area identified X-ray CT scanning as the preferred method to provide the highest resolution for true three-dimensional surface area estimates (Veal et al. 2010), but this solution requires specialized and expensive instrumentation which cannot be taken to the field and necessitates the removal and often the destruction of

the sample. These factors clearly limit the practical application of these methods for field or ongoing growth studies and restrict the involvement of volunteers and local people without scientific training or significant funding resources. The method presented in this paper does not replace these benchmark methods, but should be considered a compliment to these often more expensive and invasive techniques, for example, for monitoring coral colony size change over a period of time, followed by removal of the sample from the environment for destructive determination of actual calcification rates, or for measuring a larger sample size than would be possible with these techniques.

Here, we develop and test a method for measuring coral colony planar area measurements from photographs using equipment designed to result in minimum benthic impact, which can be easily constructed and deployed by a single diver, which achieves precision and accuracy of measurement adequate for assessing annual growth, and with processing time reduced enough to enable a single operator to reasonably rapidly analyze datasets of hundreds of images.

Materials and methods

This system is comprised of three parts: a lightweight monopod camera support, an underwater camera, and semi-automated image analysis software.

The camera support consists of a vertical member, two crossbars, and two supports which hold the crossbars perpendicular to the monopod (Fig. 1). The rigid perpendicular orientation of the hardware is essential to this method, as desired imaging plane, the length reference, and the camera sensor must be all in alignment. The primary monopod section is constructed from 150 cm length of 1.25″ aluminum round rod, cut in half, and threaded for ease of transport. The two crossbars are sections of square aluminum stock, the lower one supporting a length reference (in this case a commercial Amphibico ACWB0711 underwater white balance and color chart, but this could be any form of rigid standard length reference), and the upper one mounting the camera housing. Both crossbars run through supports made of two ~8-cm tubular sections, one round and one square, securely welded together perpendicularly, through which the monopod and crossbar slide, respectively. These supports are tapped for oversized thumbscrews with silicon-tipped ends, enabling fast but secure underwater adjustments of the position of both monopod and the two crossbars, as needed for specific shooting situations. Constructions notes, including a Solidworks schematic, for the monopod camera support device is available as Online Resource 1 or on http://vision.ucsd.edu/content/coral-colony-segmentation-and-area-measurement-tools.

Photographs were taken with either a 10-megapixel Canon Powershot G11 camera with an Ikelite 6146.12 underwater housing with a flat front lens port or a 21.1-megapixel Canon 5D Mark II with a Sea and Sea underwater housing, a 17- to 40-mm lens, and a matched acrylic dome port. Illumination was provided with either dual Ikelite DS-51 or DS-161 substrobes with diffusers. Most underwater camera housings capable of being securely mounted to a tripod can be used with this hardware. As with all scientific underwater photographs, care must be taken to assess and correct if needed for optical (lens or refraction) distortions in the image (Treibitz et al. 2012). These distortions are generally largest in image edges, and so pragmatically this distortion can be minimized by using the adjustable capability of the monopod to position both subject and length reference as close to the frame center as possible.

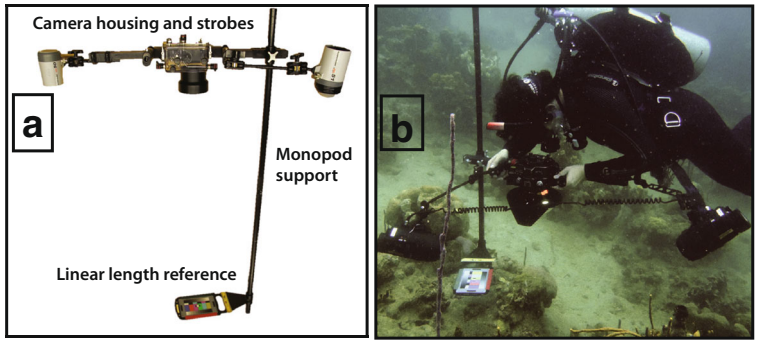

Fig. 1. **a** Monopod with camera and strobes on the top arm and length reference and color correction card attached to lower sliding support. **b** Imaging a small colony

Image analysis and area measurement were completed with a semi-automated Matlab-based program based on the algorithm GeoStar (Gulshan et al. 2010) producing both graphical and numerical output. This program allows the annotator to divide an image into areas based on common characteristics (image segmentation). Each segmented layer (Fig. 2) can be comprised of a single or multiple complex polygons. Segmentation is semi-automatic, with contours automatically generated by the software after placing strokes inside and outside of the selected area. These rapidly generated contours are then adjusted by hand for measurement. Alternatively, contours can be drawn by hand, a slower process. Layers are user-defined (e.g., live, bleached, and partially bleached tissue), non-overlapping, and edge-snapping (improving operator speed when creating multiple layers). Bleached areas can be delineated automatically with an adjustable white-saturation detection tool, decreasing processing time for images with complex patterns of bleaching. Planar area is calculated by operator annotation of the length reference in the image. Matlab code for this program and an operation manual are available as Online Resource 2 or on http://vision.ucsd.edu/content/coral-colony-segmentation-and-area-measurement-tools.

To assess planar area measurement accuracy and replicability, four independent repeated-measures tests were performed, with the photographic hardware in different configurations. The purpose of these tests was to quantify and reduce measurement error using

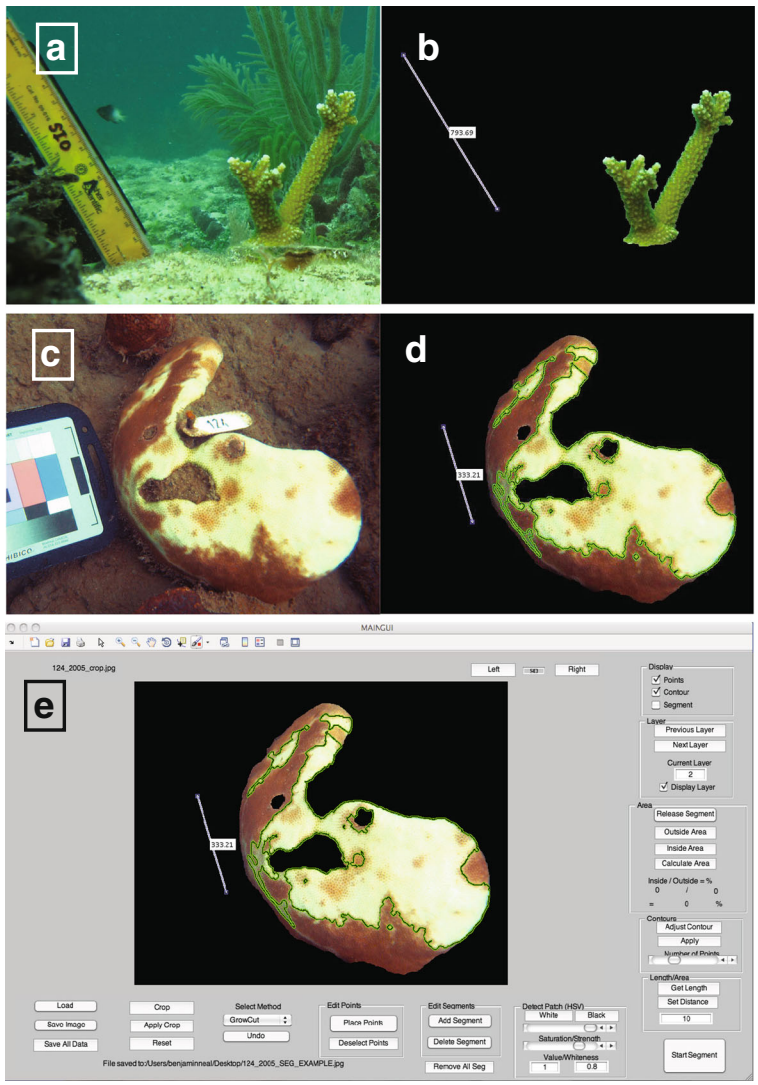

Fig. 2 Image segmentation examples using our semi-automated segmentation program, with perpendicularly fixed size reference held by the monopod (not in image frame) showing **a** horizontal image of a juvenile *Acropora cervicornis* colony from a restoration nursery, **b** same image segmented for measurement of linear extension, **c** vertical image of a tagged *Stephanocoenia michelini*, **d** same image segmented for area measurement of healthy and bleached tissue, and **e** graphical user interface of the program

configurations applicable to coral reef field conditions. Test #1 used a length reference fixed on the monopod and vertically adjusted by diver buoyancy. Two small *Siderastrea siderea* colonies (approximately 202 and 299 cm^2) were photographed ~150 times, in 4 m of calm water in Bocas del Toro, Panama. Tests #2 and #3 incorporated hardware improvements, using standardized targets (a sphere and hemisphere, both with radius of 10.8 cm and planar areas of 366.4 and 168.2 cm^2) in both pool conditions (to assess method-induced variance) and natural ocean conditions with a 1- to 2-m swell (to assess field-induced variance); test #2 added a lower slide to allow for adjusting length reference height for each target while grounding the monopod on the substrate. Test #3 improved vertical aspect control with two bubble levels mounted to control side-to-side and fore-and-aft alignment. Targets were photographed horizontally and vertically, to simulate measurement of both horizontally extending (massive or plating) and vertically extending (branching) coral morphologies. Test #4 returned to field conditions and natural subjects to quantify error expected in realistic field conditions; 23 colonies of mixed species, all massive and plating types (i.e., no branching *Acroporids*) with four genera represented, with a maximum measured mean individual colony size of 1048.11 cm^2 and a minimum of 44.98 cm^2, were independently photographed 14 times each in 3–6 m of water with a 0.5- to 0.75-m swell in varying natural light conditions at Great Guana Cay, Bahamas. For each of these four tests, repeated-measure coefficient of variation (CV) was calculated (for live area and bleached area for natural coral targets, and target area only for artificial targets), by dividing the mean by the standard deviation (SD), expressed as a percentage.

In order to compare the contribution of various error sources, comparisons were made between segmentations of different tissue types, between operators, within operators, with different camera types, between image file format types, and among repeated measurements from the same file. Differences in tissue types were made by comparing error for measurements of healthy and bleached tissue in the same colony. Inter-operator error was estimated by having two independent operators process all images from the Panama photoset used in test #1 (n = 157). Intra-operator error was estimated through random blind re-analysis of a subset of photographs by the same operator (n = 14). Variance between camera systems was evaluated by shooting duplicate photosets with the two cameras (n = 36). Resolution differences between RAW and JPG formats were determined by measuring both file types for a randomly assigned subset from the Panama photoset (n = 18). Systemic processing error was estimated by repeated blind re-analysis of a single image (n = 12). Differences in means and standard deviations for all compared datasets was performed with two-tailed Student's t tests (α = 0.05).

Results and discussion

This experiment began with the goal of tracking individual coral colony size changes following a bleaching disturbance. However, multiple initial observations taken on SCUBA with a hand-held camera without a fixed benthic framer for the camera (i.e., free swimming), with the length reference placed loose on the substrate next to the subject corals (a commonly used method), showed significant unexplained variance in various cord-length and planar area parameters taken from different photographs of the same subject (Fig. 3a). For example, the first photoset of individual coral colony images exhibited unexplained variance in planar size ranging from 2.18 to 22.12 % for the same colony. This unexplained variance rendered many of these individual observations unreliable, as the error between these observations potentially exceeded the expected annual planar area growth signal for small massive-type coral colonies typical for the area where this time series was located. Annual areal expansion was estimated at a maximum of approximately 10 % per year, given an estimated linear growth rate of 0.3–0.5 cm $year^{-1}$ for *S. siderea*, a common species in these images (Elahi and Edmunds 2007). Given that the methodological error in some cases significantly exceeded the desired signal, these images were clearly inadequate for tracking this parameter. The purpose of these experiments was to reduce this variance for measurements from simple planar projection photography to a level appropriate for replicable, rapid field assessments of coral colonies.

The first experiment (test #1—with diver buoyancy controlling the position of the length reference relative to the subject) used a naïve measurement setup, with a

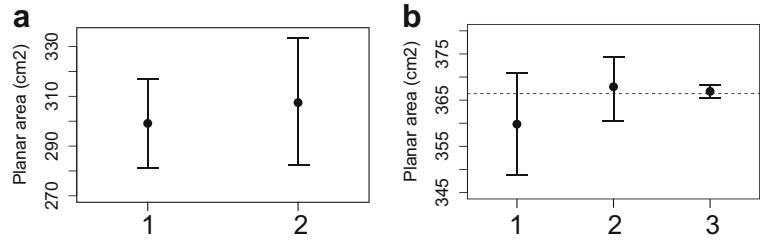

Fig. 3 **a** Mean and variance from repeated independent free-swimming underwater measurements of a single natural colony with (*1*) the length reference fixed to the monopod (mean = 299.16 cm^2, SD = 17.47, CV = 5.84 %, n = 72) and (*2*) the length reference placed directly on the benthos next to the colony (mean = 307.46 cm^2, SD = 24.75, CV = 8.05 %, n = 76). Note reduced variance with the size reference fixed on the monopod (i.e., due to being fixed parallel to the camera lens plane) and size overestimation from placing size reference on the benthos, (i.e., below the measurement plane of greatest areal extent). **b** Means and variance for repeated independent underwater measurements of an artificial hemispherical target when (*1*) free swimming with monopod (mean = 359.8 cm^2, SD = 11.01, CV = 3.03 %, n = 48), (*2*) grounding the monopod on the substrate and using the sliding adjustable reference (mean = 367.9 cm^2, SD = 6.9, CV = 1.8 %, n = 36), and (3) with bubble levels to control vertical aspect (mean = 366.9 cm^2, SD = 1.03, CV = 0.28 %, n = 42). *Dotted line* indicates actual planar area of target when viewed from directly above (366.4 cm^2). Free-swimming measurement shows underestimation from tendency to misplace the length reference above the intended plane when free-floating

randomly chosen natural target with unknown correct area solutions for the two colonies. For colony 1, the mean live pigmented coral tissue for all measurements from all photos (n = 154) was 299.16 cm^2 with a maximum observation of 351.83 cm^2 and a minimum observation of 221.63 cm^2 and a standard deviation of 27.47, yielding a coefficient of variation (CV) of 9.18 %. There was no bleached tissue area to measure on colony 1. Colony 2 had a mean live pigmented coral tissue area for all measurements from all photos (n = 160) of 202.52 cm^2, with a maximum observation of 265.89 cm^2 and a minimum observation of 126.87 cm^2 and a standard deviation of 20.81, yielding a CV of 10.27 %. The mean bleached coral tissue area for all photos of colony 2 (n = 160) was 10.42 cm^2 with a maximum observation of 14.38 cm^2 and a minimum observation of 6.51 cm^2 and a standard deviation of 1.44, yielding a CV of 22.12 %.

Foe test #2, the monopod support was modified slightly with a slider to allow for easy vertical adjustment of the length reference while grounding of the end of the monopod firmly on the substrate when framing the shot, enhancing reliability and stability of the relative planar placement of the linear length reference card. Repeated observations of a spherical artificial target in natural ocean conditions (6 m depth, sandy bottom, with strong wave surge and current) were made at a variety of aspect angles. These observations had a mean of 229.23 cm^2 for all photos (n = 16) and a standard deviation of 9.26 cm^2, yielding a CV of 3.09 %.

Test #3 addressed the issue of error introduced from aspect variation, with the monopod further modified with the addition of dual bubble levels to allow for enhanced visual vertical control while underwater. Repeated underwater independent measures of the hemispherical target were made by hand in a vertical position, resulting in a mean of 183.71 cm^2 (n = 14) and a standard deviation of 2.58 cm^2, yielding a CV of 1.4 %. This was the first experiment for which the measurements were compared to a known correct answer; the hemispherical target when viewed from the directly above had a measured actual planar area of 183.047 cm^2, giving an actual mean measurement error, if using the mean of all photos, of −0.36 %. The mean of a set of random selections of any three images from the photoset (n = 20) was −0.58 % from the known area value of the target.

Test #4 was intended to give an error estimate for measurements in working field conditions. Only live pigmented coral tissue was measured for all colonies, as no bleaching was present in these subjects. Repeat observations of 23 mixed species colonies in swell conditions yielded a mean within-colony (all colonies) CV of 2.26 % (n = 227), with a maximum within-colony mean variance figure of 3.75 % and a minimum of 0.99 %.

There was no significant difference ($t_{0.05,152}$ = 0.295, p = 0.768) in measurements of live pigmented tissue area for colony 1 between operator 1 (mean area = 298.5 cm^2 ± 1SD 27.23 cm^2; n = 77) and operator 2 (mean area = 299.81.5 cm^2 ± 1SD 27.86 cm^2; n = 77). Maximum and minimum observations were 344.91 and 351.83 cm^2 and 221.63 and 225.7 cm^2 for both

operators, respectively. There was no bleached coral tissue area on colony 1.

There was no significant difference seen in the various image factors tested except for target tissue type, with bleached tissue within-group error significantly higher than unbleached within-group error for the same colony (CV = 22.12 % vs. CV = 10.27 %, respectively; $n = 160$ for both).

There was no significant difference ($t_{0.05,158} = 0.812$, $p = 0.418$) in measurements of live pigmented tissue area for colony 2 between operator 1 with a mean area = 201.16 ± 20.16 cm^2 (±1SD; $n = 80$) and operator 2 with a mean area = 203.88 ± 21.45 cm^2 (±1SD; $n = 80$). Maximum and minimum observations were 265.81 and 283.14 cm^2 and 137.55 and 126.87 cm^2 for both operators, respectively. There was no significant difference ($t_{0.05,158} = 0.177$, $p = 0.86$) in measurements of bleached coral tissue area for colony 2 between operator 1 with a mean area = 10.44 ± 1.3 cm^2; (±1SD; $n = 80$) and operator 2 with a mean area = 10.40 ± 1.57 cm^2 (±1SD; $n = 80$). Maximum and minimum observations were 13.09 and 14.38 cm^2 and 6.66 and 6.51 cm^2 for both operators, respectively.

There was no significant difference in intra-operator measurements of live pigmented coral tissue area for colony 1 ($t_{0.05,26} = 0.909$, $p = 0.372$), shown for a repeated analysis of a randomly chosen subset for either operator 1 with the first set mean area = 303.52 ± 12.74 cm^2 (±1SD; $n = 14$) and the second set mean area 302.27 ± 11.92 cm^2 (±1SD; $n = 14$) or operator 2 ($t_{0.05,26} = 0.651$, $p = 0.521$) with the first set mean area = 305.25 ± 9.63 cm^2 (±1SD; $n = 14$) and second set mean area = 304.37 ± 10.92 cm^2(±1SD; $n = 14$).

There was no significant difference found in mean error between images taken with the two camera systems, with three trained operators each analyzing 12 images from each camera system. The mean coefficient of variation for the 10-megapixel image set (Canon G11) was 4.01 % ± 0.82 (±1SD), and for the 21.1-megapixel image set (Canon 5D Mark II) was 3.69 % ± 0.77 (±1SD). There was also no significant difference ($t_{0.05,18} = 0.286$, $p = 0.77$) from using either the RAW image files or the JPG image files for measurements of coral area. The RAW files had a mean area = 535.11 ± 9.28 cm^2 (±1SD; $n = 10$), while the JPG files had a mean area = 536.17 ± 8.84 cm^2 (±1SD; $n = 10$).

In addition to these tests, it was noted that these methods were capable of more precise measurements under ideal conditions (Fig. 3c). In calm pool water (5 m depth) while on SCUBA, with an artificial spherical target of known size and while taking care to take the best possible images, repeated-measures variance was reduced to 0.28 % ($n = 42$), with maximum actual error (measured/known planar area) for any single image of 1.6 %, and mean actual error of ±0.36 % for triplicate image sets ($n = 14$). This is potentially precise enough for monthly tracking of colony growth of fast-growing species, such as branching *Acropora* or foliose *Agaricia* species. These species are typically rapidly assessed through hand measurement of linear extension, and this method can also measure record linear extension, while also measuring planar area, enabling estimates of branch thickness to be inferred. However, correct photographic orientation is vital in this case for accurate estimates and twisting or curved branches present complications, and it is essential that planar area is not conflated with linear extension, as the two represent different parameters of growth. However, for nursery or laboratory studies, this photographic method could compliment both rapid linear extension measurements as well as more accurate but time-intensive methods such as buoyant weight measurements or more expensive three-dimensional computer tomographic (CT) scanning.

The goal of reducing the variance for measurements from simple planar projection photography to a level appropriate for replicable, rapid field assessments of coral colonies was achieved, with the repeated-measures coefficient of variance in field conditions of 2.26 % ($n = 227$). This level of precision supports the use of this method for field measurements of planar area measurements, but still represents a significant fraction of potential annual growth for many corals, and this error thus limits application of this method for short-term (less than a few months) time-series observations of size changes in corals. The following primary factors contributing to measurement error were found to be, in decreasing order (Fig. 3b): (1) incorrect vertical position of the length reference in relation to the maximum planar extent of the colony being measured, (2) misalignment of the length reference plane to the camera lens plane, and (3) inconsistent aspect of the camera to the subject. These error sources were addressed in the final monopod design, which ensured (1) correct position of vertical height of the length reference relative to the subject, (2) fixed parallel alignment of the length reference to the camera lens plane in any position, and (3) replicable vertical alignment of the camera to the

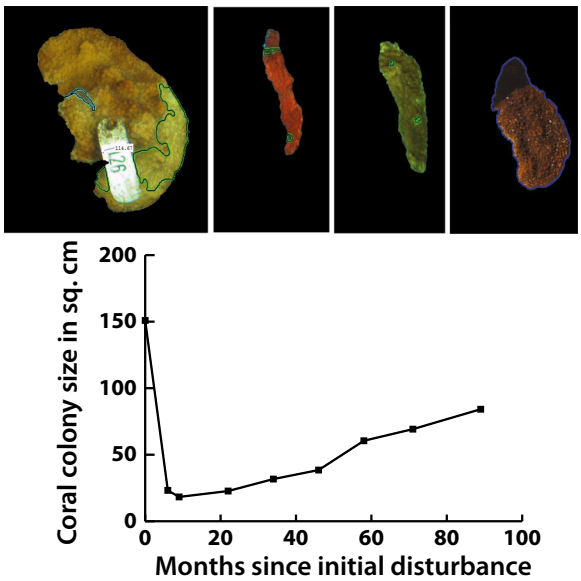

Fig. 4. Example of colony size data obtained with these methods, showing recovery from bleaching disturbance over 8 years, with segmented live tissue from 2005, 2007, 2009, and 2013. Color differences are from varying water properties and camera/lens differences and do not affect area calculations

subject. Inter-operator, intra-operator, camera type, file format, and systemic software processing error were all found to be non-significant, while tissue type (bleached vs. unbleached) choice alone resulting in a significant increase in measurement variance. There was also no significant relationship of measurement variance to colony size, up to the maximum colony size of 1017 cm^2 (r^2 = 0.03), but imaging large colonies (over ~1 m in diameter) is effectively limited by the length of the monopod and the lens and camera configurations (Fig. 4).

Conclusions

This goal of reducing in situ planar area measurement variance to a reasonable level was achieved, which supports the use of this method for field measurements of coral colony planar area, but the variance when conducting measurements in realistic field conditions still represents a significant fraction (approximately 25 % for the coral types studied) of the potential annual maximum colony area expansion signal, a level which limits application of this method for short-term (e.g., less than a few months) time-series observations of colony size changes, but should be acceptable for annual surveys of tagged colonies. This level of variance is also likely acceptable for community-size structure surveys, as this data is often binned into size classes with relatively coarse resolution.

Underwater measurements often involve reduced accuracy, simply due to the constant movement experienced while on SCUBA and to the various imaging challenges from turbidity associated with the shallow choppy conditions common to many coral sites and surf zones. These tests demonstrated that using the mean of repeated measurements of the same subject results in improved accuracy, and processing at least three independent images of each subject is recommended. It is also critical that the mechanical parallel alignment of linear length reference and the camera plane be strictly maintained for all photos and that the linear length reference is correctly and securely aligned relative to the maximum planar extent of the coral colony and the camera sensor. The mechanism for doing this must also be able to be easily and relatively precisely manipulated in diving conditions, as this adjustment of length reference height must be done individually for each photo. Using a second diver to adjust the height of the length reference for each subject while the first operator ensures vertical alignment is recommended.

In the most controlled conditions, these methods were precise enough for measurements of colony expansion for coral colonies on less than an annual basis. This application depends on the growth rates of individual species, but there may be application for this method in evaluating the growth of small colonies in both laboratory settings as well as in coral nurseries. Nursery and out-planting projects are currently gaining in popularity for re-establishing corals where the native populations have been substantially reduced or eliminated (Herlan and Lirman 2008) such as for *Acropora* species in the northern Caribbean, but the effectiveness of these efforts in terms of growth over time remains largely undocumented. The smallest coral fragments commonly used for cultivation are 2.5–3.5 cm (Lirman et al. 2010), within the size that can be imaged with these methods. More care must be taken with correctly aligning the size reference with such small subjects to avoid increased variance, and best practice would dictate using the mean of repeated measurements, which are easily taken in the same session. For branching coral propogation applications (such as for *Acropora palmata* and *Acropora cervicornis*), which have been the focus of most restoration efforts to date (Young et al. 2012), our rapid non-

invasive method is particularly suitable, given both the sensitivity if the subjects to direct manipulation and the rapid annual expected growth for these species, on the order of 73–105 cm year^{-1} (Lirman et al. 2014).

The primary benefit of the software presented here is that the interface has coral measurement-specific applications, and also that it is simplified for this task and has a shorter learning time than comparable programs like Image J or Photoshop. A similar planar area measurement can also be made using geographic information systems (GIS), some of which are now also capable of semi-supervised image segmentation, as is the software presented here. However, this semi-automated feature was rarely able to perform perfect segmentation of live coral area. Given the inherently variable light environment of the typical highly rugose coral substrate, it was difficult to take evenly lit and defined images where the entire visible colony surface presented a planar area aspect that was consistent in intensity and color and sharply defined from the background. However, this tool was helpful for generating polygons that were later hand corrected. Image processing time varied widely, from a minute or two to a half hour, for complicated colonies. Utility of this feature increased with complexity of structure, and for branching species or highly fragmented individuals, there was promise that this tool could provide a useful measurement where hand annotation might represent investing considerable effort, such as for estimating hard coral vs. enclosed habitat space on a small scale for large branching colonies. The automatic bleaching detection tool (based on a sliding white balance tool) did reduce processing time when delineating bleached area in pictures, particularly for complex and scattered bleaching patterns seen in many species, such as *Montastrea* spp., although the resulting delineation of bleaching usually also required hand corrections. Even with this, measurements of bleached coral tissue exhibited much higher variation in these experiments than did the live area measurements. This is likely from both actual differences in the presentation of the bleached area under differing lighting and water quality conditions, as well as the lack of a specific spectral definition of bleached tissue, which was determined subjectively by each operator. The semi-automated processing tool automatic bleached area detector did rapidly select these areas, but this is equipped with a sliding intensity scale, and thus, while being automated, is equally subjective. There is also a natural spectrum of color in both healthy and bleached coral tissue, and thus deciding on an absolute spectral definition for the bleached parameter was found to be not possible and achieving consistency within a research group on the definition of bleached coral area through discussion, examination of results, and familiarity with the species of concern is paramount for achieving ecologically sound and useful results. The system was found to be most accurate in measurements of live, healthy, fully pigmented coral tissue, and the use of any automated bleaching detection tool for coral studies must thus be exercised with caution.

Another significant limitation in interpretation of these in situ measurements is that planar area has been shown to often not translate directly to surface area across species or colony sizes (Naumann et al. 2009), which is in many cases a more meaningful description of coral biomass for species with significant three-dimensionality. However, given the difficulty in attaining accurate three-dimensional measurements underwater and that measuring this parameter directly usually involves invasive impact to the living coral, planar area can serve as a more attainable measure, but not as a replacement. However, development of a species-specific and size-specific conversion parameter for estimating 3D surface area from accurate planar area for a given study can in some cases allow for a surface area proxy to be calculated (Holmes 2008).

Compared to making hand measurements underwater, having a permanent photographic record facilitates making later multiple measurements (linear extension, branch width, total colony height, etc.) and allows for re-analysis of images, if needed. It was shown to be not necessary to use an expensive camera system for this measurement. Rather, in place of purchasing a costly large format single-lens reflex (SLR) camera, a focus by the operator on careful control of the alignment factors described above, along with careful attention to supplemental light and correct photographic exposure and focus, will result in images from almost any consumer camera from which reasonably accurate data can be derived.

In conclusion, this method can yield insights into differing coral growth, survival, and mortality trends across time and space, but within the bounds of the variance rates expressed here, taken as a function of the expected growth rates for the species in question. Both the custom fabrication of the monopod apparatus as well as the purchase of the camera and underwater housing should be within financial limits for most

researchers. With only simple hand-carried equipment, this method is useful for remote sites, single-operator studies such as student work, and community-based monitoring efforts operating under restrictions of time and money. Two-dimensional, planar projection photography can thus be employed as a simple, rapid, and inexpensive method for accurately assessing a number of coral growth or community parameters, with applications including inter-annual time series observations for individual colony expansion, fragmentation, or mortality; quantitatively monitoring and measuring the extent of bleaching and disease impacts in individual colonies of a larger population; and describing community size structure of small- to medium-sized coral colonies for a given area.

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