Acropora cervicornis Metrics for Quantifying the Size and Total Amount of Branching Coral

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ACROPORA CERVICORNIS METRICS FOR QUANTIFYING THE SIZE AND TOTAL AMOUNT OF BRANCHING CORAL

By

Courtney Kiel

A THESIS

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ACROPORA CERVICORNIS METRICS FOR QUANTIFYING THE SIZE AND TOTAL AMOUNT OF BRANCHING CORAL

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Acropora cervicornis, listed as threatened under the US Endangered Species Act, is a branching coral with a complex morphology that does not readily conform to traditional metrics of colony size and percent cover. Commonly used metrics do not reflect the functional scale of this coral’s structure nor unit requirements required by the Endangered Species Act that calls for accurate and defensible metrics to quantify and monitor change in the remaining viable populations. Existing metrics for measuring branching corals are both time-consuming and variable. Therefore, the goal is to streamline and calibrate in situ measurements of A. cervicornis colonies and explore the ability to estimate arduous metrics of colony morphology from easy-to-measure attributes. It is demonstrated, based on measurements made in the upper Florida Keys, that colony volume, surface area, percent cover, and total linear extension of branching tissue can be reliably approximated from simple in situ measurements of 1) colony height, 2) maximum branch diameter, and 3) a top-down colony photo ($R^2 > 0.90$ for all estimations). Furthermore, these relationships were consistent among natural wild colonies, as well as experimentally transplanted and nursery-reared, outplanted colonies thus indicating the robustness of the relationships between colony morphometrics in both natural and restored corals in this region. This standardized, repeatable, defensible and efficient protocol for monitoring
*A. cervicornis* colonies capitalizes on the relationships among colony attributes documented here.
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Executive Summary

Corals are declining in the Caribbean due to natural and anthropogenic impacts. Some species such as *Acropora cervicornis* may even be approaching extinction (NMFS 2006). This is alarming, this coral plays an important role in the marine ecosystem by providing architectural structure that benefits numerous other species (Holbrook et al. 2002, 2008). Additionally, it has many direct links to ecological and economic services, including reef growth, island formation, coastal protection, fisheries habitat, biodiversity, and even nutrient cycling (Precht 2006). Extinction of this species would likely have a negative domino effect on the ecosystem and these services.

*Acropora cervicornis* is commonly known as staghorn coral due to its complex, branching shape. In 2006 staghorn coral was listed as a threatened species under the US Endangered Species Act (NMFS 2006). This Act requires accurate data to quantify and monitor change in the remaining populations and to evaluate attempts to restore and delist the species. Therefore consistent, repeatable measures are needed to assess its abundance and how the populations are changing.

Projected (2 dimensional) coral cover, measured either as absolute area or percent cover, has traditionally been used to monitor coral populations because it is tractable to measure in the field and it has been used in publications for years (Rogers et al. 1994; Gardner et al. 2003; Lang 2003; Brown et al. 2004; Viehman et al., 2009). However, it is apparent that projected benthic cover does not work for branching corals (Bak & Meesters 1998, 1999). In addition, existing metrics for measuring branching corals are both time-consuming and variable. Therefore, the goal of this study is to streamline *in situ* measurements of *A. cervicornis* colonies and explore the ability to estimate arduous metrics of colony morphology from easy-to-measure attributes.
To accomplish this, I predicted that the time-consuming measure of total linear extension (TLE) could be reliably approximated from skeletal ellipsoid volume (based on length, width, and height dimensions) of the coral colony. TLE is perhaps the most straightforward, intuitive parameter for the ‘amount of coral’ in a branching colony, but ellipsoid volume is a much faster in situ estimate (Fig. 1).

The robustness of this relationship was explored by comparing colony TLE to colony ellipsoid volume among wild colonies, experimentally transplanted colonies, and restored colonies from a coral nursery to determine if the patterns held regardless of colony origin. Second, colony surface area (calculated from the field-measured TLE and maximum branch diameter) was explored to see if it could be consistently approximated from ellipsoid volume and maximum branch diameter. To conclude, it is suggested that in situ sampling time can be reduced by capitalizing on the consistent relationship among colony attributes, leading to a more standardized, repeatable, defensible, and efficient protocol.

Therefore, it is demonstrated that simple in situ measurements of 1) colony height 2) max branch diameter and 3) a top-down colony photo can provide a reliable prediction of colony (three-dimensional) volume and total linear extension of branching tissue ($R^2 > 0.90$ for all estimations) (Fig. 4-8). Furthermore, these relationships were consistent among natural wild colonies, as well as experimentally transplanted and nursery-reared colonies indicating the robustness of the relationships between colony shape metrics.

This protocol provides a scalable, repeatable, defensible, and consistent proxy for architectural complexity and, consequently, habitat value. Thus by streamlining and standardizing monitoring efforts of branching corals researchers and managers can more
confidently quantify the population and apply this architectural metric to restoration efforts (required under the Endangered Species Act and the Natural Resource Damage Assessment) and service estimates.
Chapter 1: Introduction

As coral populations continue to decline in the Caribbean, consistent, repeatable parameters are needed to assess abundance. These measures are essential for Acropora cervicornis because it is threatened with extinction (NMFS 2006). In addition, its complex branching morphology makes traditional demography metrics less informative and difficult to assess (Bak & Meesters 1998, 1999). Therefore, more stringent and justified metrics are needed to implement statutory protections that have already been applied to A. cervicornis, including monitoring and active restoration efforts.

In 2006, A. cervicornis was classified as threatened species under the United States Endangered Species Act (ESA) (NMFS, 2006). The ESA provides legal mandates to ‘recover’ listed species populations and to protect their critical habitats independent of their ‘habitat services’. The goal of the ESA is to conserve the ecosystems upon which endangered species and threatened species depend, and to take steps necessary to achieve these purposes (16 USCA 1531 (b)). Consulting or mitigating actions that involve a ‘take’ of the species require an appropriate ‘unit’ definition for branching corals that is not straightforward because of its complex branching morphology and colonial life form.

The ability to make accurate estimations of colony area from simple field measurements provides a valuable tool for characterizing these attributes, functions and values of coral reef ecosystems (Loya 1972; Courtney et al 2007). The metric most often used for scientific, monitoring, and management applications is projected (2D) coral cover (either as absolute area or percent cover) because it is tractable to measure in the field and it has been used in publications for years (Rogers et al. 1994; Gardner et al. 2003; Lang 2003; Brown et al. 2004; Viehman et al., 2009). However, projected benthic cover does not accurately represent branching corals such as A. cervicornis because many
corals have bouldering or plate like morphologies while Acroporids are highly branched. There are other methods addressing morphometric measurements. For instance, Marsh (1970) estimated actual 3D surface area either by the weight difference of an object before and after being wrapped in aluminum foil or from direct measurement of the unwrapped aluminum foil; Meyer and Schultz (1985) used a similar method with latex; Hoegh-Guldberg (1988) used dye, and Stimson and Kinzie (1991) used wax. These methods along with computer intensive models are time consuming and not feasible for monitoring purposes (Bythell et al., 2001, Courtney et al., 2007).

Additionally, architectural structure and habitat provided by this branching coral in the form of refuge space helps drive the tropical distribution and abundance of reef fishes (Holbrook et al, 2000, 2002, 2008; Kane et al. 2009; Schmitt et al. 2009). Measurements in three dimensions (3D) are useful for quantifying coral size or biomass, as well as a host of functional parameters related to surface area such as photosynthetic activity, feeding, respiration, growth, or calcium carbonate deposition (Crossland et al., 1991; Davies 1980; Kinsey 1977; Dahl 1973; Goreau 1963; Odum and Odum 1955). Additionally, reef complexity and live surface area available for growth and reproduction can also lend insight into reef-building capacity and sustainability (Done 1997). Thus, *in situ* 3D measurements of this morphologically complex coral would be much more informative than the more common and unit-less estimate of percent cover.

Total linear extension (TLE) is perhaps the most straightforward parameter for the ‘amount of coral’ in a colony composed of cylindrical branches (Fig. 1). TLE is measured by summing all lengths of the branch, and the sum of all branches (skeletal extent) gives total linear extension (cm) (Shinn 1966). However, this method is time consuming to
complete in the field so calibrations are needed to make more feasible and efficient *in situ* estimates of this parameter.

Active restoration has already been employed to address the depleted state of *Acropora cervicornis* (Johnson et al. 2011). Nursery cultured colonies and wild transplants have been placed along the investigated reef sites to try and preserve unique genetic lineages, produce corals for research, and undertake reef restoration projects (Coral Restoration Foundation). Nursery reared and transplanted corals are outplanted to reseed surrounding reefs with genetically diverse lineages and rehabilitate injured corals. One goal of this study is to determine if restored and wild colonies require different monitoring protocols.

Here, the possibility of simplifying field methods used to reliably generate metrics of *A. cervicornis* colony attributes are explored. In particular, more efficient protocols for estimating colony volume of restored and wild colonies are investigated. First, it was determined if the intuitive, yet time consuming measure of total linear extension (TLE) could be reliably approximated from colony ellipsoid volume (EV). Second, the robustness of this relationship is explored by comparing wild colonies, experimentally transplanted colonies, and restored colonies from a coral nursery to determine if the patterns held regardless of colony origin. Finally, I conclude by suggesting that *in situ* sampling time can be reduced by capitalizing on the relationship among colony attributes to create a more standardized, repeatable and efficient protocol for determining size metrics of *A. cervicornis*. 
Chapter 2: Materials and Methods

Study Sites and Field Measurements. Live colonies of *A. cervicornis* (staghorn coral) have been transplanted at a range of sites along the Florida Reef Track over a period of three years (2008-2012) for both nursery reared (K.Nedimyer, pers. comm.) and direct transplants (M.Miller, unpubl) purposes. Transplanted colonies were measured at six different sites. Wild colonies were measured at two additional sites between May 2011 and January 2012 (Table 1).

Healthy colonies (minimal partial mortality) were selected to represent a range of sizes (range: 6 to 1,910 cm TLE) to explore relationships between the accuracy of the different metrics and colony size and complexity. For each selected colony, the following colony dimensions were measured: maximum colony diameter (Length, in cm), perpendicular to max diameter (Width, cm), maximum colony height (cm) above the benthos, maximum branch diameter (generally of a basal branch, mm), and total linear extension (TLE, cm) of branch skeleton, were measured (See metrics in Table 2). A scaled digital photograph was taken downward from above each colony. A meter rod (L, W, H), flexible meter tape (TLE), and calipers (branch diameter) were used for measurements. Three colonies were re-measured during the same dive by the same observer to verify repeatability of the *in situ* measurements. In total, 79 corals were measured from 8 sites, including 14 wild colonies and 65 transplanted colonies.

Derived Parameters. A range of metrics were derived from the field measurements and are summarized in Table 2. Once branching corals grow to a certain size, their overall shape resembles an ellipse. Therefore the maximum length, width, and height were used
to calculate an estimated colony ellipsoid volume:

$$EV = \frac{4}{3} \pi H \times L \times W$$

The approximate surface area (SA) is calculated using the cylindrical surface area equation:

$$SA = 2 \pi r^2 + 2 \pi r h$$

where $h =$ calculated TLE and $r$ is 1/2 max diameter.

**Photographic Analysis.** Projected percent cover, projected area, and projected ellipsoid area of the colony were derived from analysis of the photograph of each colony. For projected percent cover, the annotate tool in Mac Preview was first used to create an ellipsoid of the colony (Figure 2a). An effort was made to stay consistent with field measurements by aligning end points of the ellipsoid to the farthest length and width branch. CPCe software was then used to analyze projected percent cover of the colony using 20 random points (Pante and Dustan 2011). Points were scored as one of three categories: (1) ‘live’ *A. cervicornis* tissue (2) a ‘miss’ corresponding to a point within the ellipsoid outline of the colony yet not falling on live coral, or (3) ‘out of bounds’ corresponding to a point outside of the ellipsoid outline of the colony. Projected coral cover was then calculated as:

$$(\text{no. of ‘live’ points/ (no. of ‘live’ + ‘miss’ points)}) \times 100$$

This approach to percent cover allowed me to estimate percent live coral projected within the outline of the colony.

To calculate the projected (2D) area of the colonies, the pictures were first scaled using the calibration tool in CPCe to the scale bar in the image. The outline of the actual
coral branches were then traced as close as possible to give the calculated top-down projected area of the coral (Fig 2c). The same was done to measure the estimated elliptical footprint area (Fig. 2d).

An additional estimate of ellipsoid volume was calculated from the photo-derived elliptical area encompassing the length and width of the colony multiplied by the field-measured height of the colony (Table 2).

**Analysis.** Data sets were checked for normality using Shapiro-Wilk tests, and log$_{10}$ transformed to meet assumption of normality. Outliers removed were colonies considered too large to accurately measure the TLE. For all analyses, time-costly measurements such as TLE were designated as dependent variables and the derived parameters were designated as independent variables. Simple linear regression analysis was used to test for the degree of association between field measured TLE and EV, calculated TLE and maximum SA, TLE and photographically-derived elliptical and colony area, and TLE and projected percent cover estimates. Residual plots were examined to assess the precision of regression models (Sokal and Rohlf 1995). Separate regressions of TLE and EV were also performed for colonies of different origin or from different reef types and homogeneity of slopes was tested to explore the robustness of relationships between the reef type and colony origin. Error graphs examined the distance between the data points and the hypothesized regression model to investigate the relationship among the entire population of sampled coral colonies for TLE and colony EV.
Chapter 3: Results

Seventy-nine corals were measured from 8 sites, including 14 wild colonies, 42 transplanted colonies for restoration, and 23 experimentally transplanted colonies between June 2011- January 2012. All measurements differed by < 7.4% between duplicate measurements on corals made by a single observer (n=3) indicating minimal human measurement error.

Projected Percent Cover of the colony is not predictive of the total linear extension ($R^2=0.00$; Fig.3) likely due to the large void space as an artifact of the complex colony morphology. Percent cover is most commonly used to address communities of coral and not individual coral colonies which may account for the lack of relationship.

Colony Ellipsoid Volume was a strong, positive predictor of the total amount of coral (TLE) for all non-outlier colonies $\log_{10}$ transformed ($R^2 = 0.936$; Fig. 4), for all colonies (including outliers) ($R^2=0.806$; Fig.5), for wild colonies ($R^2 = 0.939$), for experimental colonies ($R^2 = 0.952$), and for restoration colonies ($R^2 = 0.942$; Fig. 7). Thus, tractable field measurements of height, length, and width (cm) can provide a highly accurate estimate of the total amount of coral (TLE) in cm when the data is first $\log_{10}$ transformed and large colony outliers removed. Parameters for all colonies are significantly correlated with a $P<0.0001$ giving a linear fit of:

$$\text{Log(EV)} = 0.1740514 + 1.551083 \times \text{Log(TLE)}$$
Other shapes for estimating volume were explored such as cylinder, ellipsoid, or rectangular, but the $R^2$ was lowest for the ellipsoid shape. Therefore an ellipsoid volume was used due to its visual resemblance to the natural growth of the colony.

**Homogeneity of slopes analysis** was used to compare the relationship between estimated EV and actual TLE among 1) reef types and 2) colony origins (Fig. 6 and 7). Slopes are not significantly different among all three reef types ($P = 0.069$) and colony origin ($P < 0.0001$). However, there is a steeper slope for deep reef and patch reefs, shallower slope for shallow forereef habitats, and colony origin affects the relationship between TLE and EV parameters particularly with smaller colonies. The difference in these slopes becomes much more apparent when the data are not transformed, however there is a strong overall correlation (Fig. 5).

**Approximate Colony Surface Area** was derived from a calculated TLE and field measured maximum branch diameter. It is strongly correlated with colony TLE (measured in the field) ($R^2 = 0.939$; Fig. 8). Tractable field measurements of height, length, width (cm$^3$), and max diameter (mm) can provide a consistent estimate of maximum surface area when the colony is under a certain size. Differences between actual and estimated total linear extension and calculated surface area were explored using a bivariate fit test (Fig. 9). These are significant relationships where error increases with colony size, indicating a size limitation to this approach. A graphical visual estimate suggests the maximum total linear extension of 750 cm should be used to avoid a size colony threshold that this relationship can reasonably estimate. Meaning the statistic
between the data and the assumed true hypothesis seems too distant for these larger colonies.

Utilizing Coral Point Count with Excel extensions (CPCe) to analyze photographs reduces the need to take time consuming *in situ* measurements. Projected ellipsoid area multiplied by field measured height is a strong, positive predictor of field measured ellipsoid volume ($R^2=0.912$) indicating that *in situ* measurements can be reduced to colony height and maximum branch diameter to complement CPCe measurements taken from a top down colony photo (Fig. 10).
Chapter 4: Discussion

It is possible to streamline and calibrate in situ measurements of *A. cervicornis* colonies that accurately estimate arduous metrics of colony morphology from easy-to-measure attributes based on a population including both transplanted (restored and experimental) and wild in situ colonies in the upper Florida Keys, and spanning midshore patch reef (<7m depth), shallow fore-reef (~7 m) and deeper fore reef (15-18m depth) habitats. Therefore, this study provides a protocol for estimating colony TLE and colony ellipsoid volume from 2 simple in situ measurements of: 1) colony height and 2) a photo taken top-down ($R^2 > 0.90$ for all estimations). This protocol is a very efficient monitoring tool because accurate estimates of 3D size and structure of corals directly relate to many values and functions of coral reefs (Loya, 1972; Courtney et al. 2007). An additional parameter estimating colony surface area may also be made with the additional field measurement of branch diameter. Such tractable surface area estimates may be useful in scaling functional aspects of the colony such as productivity or fecundity.

Using photographic areal estimates allows for a faster in situ sampling time, but greater post-processing effort to arrive at estimates. It is usually desirable to quickly sample as many corals as possible because field time is often costly. Analysis can then be done in the office with the same level of statistical precision. However, similar precision is obtained by estimating colony volume from field measurements of length and width or from area derived from a photograph.

The ACER protocol capitalizes on the relationships among colony attributes making monitoring efforts more standardized, repeatable, defensible and efficient. Consistency gives promise that similar relationships may hold for other populations of *A.*
Acropora cervicornis colonies, and possibly even other species of branching coral, though this remains to be validated. In the future, we hope to collect additional data for colonies in other regions such as Glovers Reef lagoon, Belize and the Dry Tortugas, Florida.

Habitat type could be considered when following this ACER measurement protocol because it seems to influence the morphology of corals. The slope between estimated EV (cm$^3$) and actual TLE (cm) is steeper for deep reefs and patch reefs, shallower slope for shallow forereef for the relationship between TLE and EV parameters. However, the overall relationship (including outliers) is very strong with an $R^2$ of 0.8063 and a $P < 0.0001$ therefore the differences in slope can be ignored because they are not significant. It is likely that depth, water motion, bottom type, adjacent habitat, competitors, and anthropogenic impacts all slightly influence growth and thus morphology of this particular species.

Projected 2D estimates of coral cover that were previously used clearly do not accurately represent ‘amount’ of branching staghorn coral, at least at the scale of the colony. Researchers and resource managers can more accurately and efficiently monitor this ESA listed species using a 3D estimate that warrants regulatory requirements for understanding the viable population size, how the population is changing, and how to account for unwarranted losses of *Acropora cervicornis*. Mitigation efforts may also benefit from this ACER measurement protocol because restoration planning would be more standardized.

In addition to ESA mandates, this protocol provides a scalable proxy for architectural complexity and, consequently, habitat value that may be useful for Natural Resource Damage Assessment mandates. Particularly, service-to-service approaches,
such as Habitat Equivalency Analysis (HEA) use an ecological metric, rather than dollars, to estimate damages. When looking specifically at HEA applications, Piniak et al. (2009) suggests a need for an informative metric on quantifying amount of complex architectural habitat in branching coral morphologies. This metric or unit is defined here in this paper and satisfy the need for a tractable architectural metric for quantifying the total amount of coral (TLE).

To conclude, 1) projected 2D percent cover does not accurately represent the ‘amount’ of staghorn coral and 2) estimates of a 3D ellipsoid volume accurately related to the actual amount of branching coral. Now, monitoring of this particular species can be more efficient, standardized, and defensible.
LITERATURE CITED


Loya Y (1972) Community structure and species diversity of hermatypic corals at Eilat, Red Sea. Marine Biology 13:100-113


FIGURES

**Figure 1.** Picture of *A. cervicornis* colony. The red stick figure depicts how total linear extension (TLE) was measured for that branch a+b+c+d (all branches summed for the colony). The sum of all branches (live and dead) gives total linear extension (cm).

**Figure 2.** Stepwise analysis of top-down photo area conducted using CPce. A) Elliptical outline applied around edges of coral colony. B) Image is scaled using in situ meter rod. C) Coral colony is traced giving top-down actual surface area. D) Elliptical shape is traced, giving top-down elliptical surface area.
Figure 3. Relationship between percent cover and total linear extension calculated using CPCe.

Figure 4. Relationship between log_{10}-transformed total linear extension (cm) and log_{10}-transformed ellipsoid volume (cm^3) with outliers removed. Metrics are significantly correlated with an R^2 of 0.936 and a P<0.0001. \[ \text{Log}(EV) = 0.1740514 + 1.551083 \times \text{Log}(TLE). \]
Figure 5. Relationship between total linear extension (cm) and ellipsoid volume (cm$^3$) with outliers. Metrics are correlated with an $R^2$ of 0.8063 and a $P < 0.0001$, however variance around the regression line is not constant. \( EV (\text{cm}^3) = -3941.525 + 58.942362 \times \text{TLE (cm)}. \)

Figure 6. Homogeneity of slopes analysis addressing the regression relationship between estimated \( EV (\text{cm}^3) \) and actual \( \text{TLE (cm)} \) are constant among varying reef type, but the slope is not constant ($P = 0.0690$).
Figure 7. Homogeneity of slopes analysis addressing the regression relationship between estimated EV (cm$^3$) and actual TLE (cm) are constant among varying colony origins (P < 0.0001).

Figure 8. Relationship between log$_{10}$-transformed total linear extension (cm) and log$_{10}$-transformed derived surface area (cm$^2$) with outliers removed. Metrics are significantly correlated with an R$^2$ of 0.931 and a P<0.0001
**Figure 9.** Error graphs exploring the difference between actual and estimated TLE (cm) and SA (cm$^2$) using a bivariate of fit test of the differences (TLE by TLE and SA by SA respectively). The estimated TLE is on the y axis and the actual is on the x axis.

**Figure 10.** Photographic estimated EV (cm$^3$) is strongly correlated to field measured EV (cm$^3$) for all colonies with a P<0.001. Scale bars are in thousands.
TABLES

Table 1: Site name, Global Positioning System Coordinates, and depth in meters of study sites, all located in the Upper Florida Keys.

<table>
<thead>
<tr>
<th>Site</th>
<th>Reef Type</th>
<th>Coordinates</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquarius</td>
<td>Deep forereef</td>
<td>24°57.010N, 080°27.130W</td>
<td>18</td>
</tr>
<tr>
<td>Conch Shallow</td>
<td>Shallow forereef</td>
<td>24°57.083N, 80°27.594W</td>
<td>5</td>
</tr>
<tr>
<td>Pickles</td>
<td>Shallow forereef</td>
<td>24°59.170N, 080°24.940W</td>
<td>9</td>
</tr>
<tr>
<td>Molasses</td>
<td>Shallow forereef</td>
<td>25°00.740N, 080°22.400W</td>
<td>9</td>
</tr>
<tr>
<td>French</td>
<td>Shallow forereef</td>
<td>25°02.057N, 080°20.893W</td>
<td>9</td>
</tr>
<tr>
<td>Key Largo Dry Rocks</td>
<td>Patch reef</td>
<td>25°07.20N, 080°18.000W</td>
<td>6</td>
</tr>
<tr>
<td>Tavernier Patch A</td>
<td>Patch reef</td>
<td>24°59.228 N, 80°27.173W</td>
<td>5</td>
</tr>
<tr>
<td>Tavernier Patch B</td>
<td>Patch reef</td>
<td>24°59.242N, 80°27.159 W</td>
<td>5</td>
</tr>
<tr>
<td>Little Conch</td>
<td>Patch reef</td>
<td>24°56.550N, 080°28.430W</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2: Summary of metrics and how they were derived.

<table>
<thead>
<tr>
<th>Metric Units</th>
<th>Unit</th>
<th>How it was measured</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>Colony Length (L)</td>
<td>cm</td>
<td>Maximum colony diameter</td>
<td>Field measured</td>
</tr>
<tr>
<td>Colony Width (W)</td>
<td>cm</td>
<td>Perpendicular to maximum colony diameter</td>
<td>Field measured</td>
</tr>
<tr>
<td>Colony Height (H)</td>
<td>cm</td>
<td>Length between benthos and top of colony</td>
<td>Field measured</td>
</tr>
<tr>
<td>Branch Diameter</td>
<td>mm</td>
<td>Maximum branch diameter (usually basal branch)</td>
<td>Field measured</td>
</tr>
<tr>
<td>Colony Total Linear Extension (TLE)</td>
<td>cm</td>
<td>Sum of all branch lengths of colony</td>
<td>Depiction in Figure 1</td>
</tr>
<tr>
<td>Calculated Total Linear Extension</td>
<td>cm</td>
<td>Calculated from regression of EV with colony TLE measured in the field</td>
<td>Log(EV) = 0.1740514 + 1.551083*Log(colony TLE)</td>
</tr>
<tr>
<td>Colony Ellipsoid Volume (EV)</td>
<td>cm³</td>
<td>Calculated from L,W,H</td>
<td>EV=(4/3)×π ×H×L×W</td>
</tr>
<tr>
<td>Derived Colony Surface Area</td>
<td>cm²</td>
<td>Calculated from field measured branch diameter and calculated TLE</td>
<td>SA= 2 π r² + 2 π r h where r² = ½ max. diameter and h= calculated TLE</td>
</tr>
<tr>
<td>Projected</td>
<td>cm³</td>
<td>Photo derived using CPCe</td>
<td>Digitized area of ellipse drawn</td>
</tr>
<tr>
<td>Measurement</td>
<td>Unit</td>
<td>Data Source</td>
<td>Calculation</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------</td>
<td>------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Ellipsoid Area</td>
<td></td>
<td></td>
<td>around the colony outline (Fig 2d)</td>
</tr>
<tr>
<td>Projected Colony Area</td>
<td>cm²</td>
<td>Photo derived using CPCe</td>
<td>Digitized area of branches outlined on photograph (Fig 2c)</td>
</tr>
<tr>
<td>Projected Percent Cover</td>
<td>N/A</td>
<td>Photo derived using CPCe</td>
<td>Proportion of random points within colony elliptical outline that intersect live tissue (no. of ‘live’ points/ (no. of ‘live’ + ‘miss’ points)) * 100</td>
</tr>
</tbody>
</table>
### ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACER</td>
<td><em>Acropora cervicornis</em></td>
</tr>
<tr>
<td>ESA</td>
<td>Endangered Species Act</td>
</tr>
<tr>
<td>HEA</td>
<td>Habitat Equivalency Analysis</td>
</tr>
<tr>
<td>TLE</td>
<td>Total Linear Extension</td>
</tr>
<tr>
<td>EV</td>
<td>Ellipsoid Volume</td>
</tr>
<tr>
<td>SA</td>
<td>Surface Area</td>
</tr>
<tr>
<td>CPCe</td>
<td>Coral Point Count with Excel extensions</td>
</tr>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
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</table>