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Estimating three-dimensional surface areas on coral reefs

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ABSTRACT

One of the main obstacles for biological assessments of coral reefs over large spatial scales is the ability to link data obtained at the laboratory scale to spatially large data sets. This is particularly the case when trying to assess the ecological function of microbial processes following dramatic large-scale events such as mass coral bleaching. To be able to infer ecological function of field corals from laboratory measurement standardised to surface area it is imperative to be able to measure the actual surface area of corals in-situ. There have been several approaches proposed to estimate the three-dimensional surface area of field corals. While these have been shown to be reliable for simple coral growth forms, large degrees of error are introduced when applying them to complex growth forms. This paper refines a technique for calculating the three-dimensional surface area based on the projected surface area, with errors associated with complex growth forms reduced to <5%. Once developed, the simple mathematical relationship (called the surface index) can be used to estimate the three-dimensional surface area of field corals from photograph or video imagery, allowing physiological parameters of corals determined at the sub-colony scale to whole colony and spatially large data sets of coral reefs. The effectiveness of using laser scanning techniques to derive three-dimensional images of corals is also discussed.

1. Introduction

To improve the understanding of coral reef ecosystems, it is essential that studies are conducted over a wide range of temporal and spatial scales. It is equally important that scientists are able to apply (or infer) findings from studies conducted at one scale to studies at other scales (i.e. the ability to scale up (or down)). Indeed, the ability to extrapolate small scale processes has been identified as the next challenge in microbiology (Paerl and Steppe, 2003). With the rapidly increasing interest in microbial processes and how they influence ecosystems at different scales, this need has become even more urgent and necessary to resolve. Inter-study evaluations and extrapolations require that measurements are normalised to a variable that allows for simple comparisons. In the case of coral biology, several possibilities have been used for normalising physiological parameters such as tissue biomass, zooxanthellae density, chlorophyll density and respiration. Previously proposed parameters include colony (Yonge et al., 1932), colony weight (Kawaguti, 1937) and coral polyp (Marshall, 1996). The most common standardising parameters however are surface area and tissue biomass (Edmunds and Gates, 2002). While there are many arguments for the use of biomass as a suitable standardising parameter (Edmunds and Gates, 2002), surface area is most suited for the integration of in-situ measurements and spatially large scale data sets as biomass measurements are not feasible in these situations.

The ability to estimate the surface area of both biotic and abiotic surfaces is an essential component of many facets of biology including the capacity to relate findings across spatial scales. Nowhere is this more evident than in the field of coral reef biology and there have been several methods proposed to estimate three-dimensional surface areas of coral surfaces (Table 1). Traditionally, the two-dimensional projected area was used as a measure of surface area for the calculation of ecological budgets (Kanwisher and Wainwright, 1967; Odum and Odum, 1955) with "correction factors" introduced in order to bring values up to more realistic levels (Webb et al., 1975; Wilkinson et al., 1984). For example, Odum and Odum (1955) used the projected area for calculation of biomass and chlorophyll levels but scaled by a factor of three for bacterial estimates in their study on Eniwetok Atoll. In 1970, Marsh (1970) described a method for estimating the actual three-dimensional surface area. This involved covering an object with aluminium foil and estimating the surface area either from the weight difference of the object being measured (with the weight per unit area of the foil previously determined) or by unwrapping the object and spreading the foil flat to make a direct measurement. For many years this was the most popular method of determining surface area (Hoegh-Guldberg, 1988). Other methods based on this idea have since been developed including coating with latex (Meyer and Schultz, 1985), dye (Hoegh-Guldberg, 1988) or paraffin wax (Stimson and Kinzie, 1991), the latter being one of the common methods currently used. While each of the currently utilised methods provide a good estimation of the three-dimensional surface area, they are only practical at the relatively small scale of the coral nubbin or small colony and few methods can be made on live, in-situ colonies. While this does not present a problem

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Table 1
Published methods for estimating the surface area of corals

Methodology	In-situ measurements	Colony scale measurements	Reef scale measurements	Accuracy	Reference
Projected area	Yes	Yes	Yes	Poor	Kanwisher and Wainwright (1967), Odum and Odum (1955)
Aluminium foil	No	Limited	No	Good	Marsh (1970)
Calculation	Yes	Yes	Yes	Poor	Chancerelle (2000), Dahl (1973), Alcala and Vogt (1997), Courtney et al. (2007), Fisher et al. (2007)
Latex	No	Limited	No	Good	Meyer and Schultz (1985)
Scanning	No	Limited	No	Very Good	Kaandorp and Kuebler (2001)
Dye uptake	No	Yes	No	Good	Hoegh-Guldberg (1988)
Waxing	No	Limited	No	Good	Stimson and Kinzie (1991)
Photogrammetry	Yes	Limited	No	Time constrained	Bythell et al. (2001)
3-D reconstruction using video	Yes	Limited	No	Time constrained	Cocito et al. (2003)

for many applications of three-dimensional surface area data, when estimates over large colonies or even whole reefs are required, these methods become impractical due to the inability to make unobtrusive measurements.

It is now recognised that like many terrestrial and aquatic ecosystems, coral reefs are under significant pressure throughout their distribution, with many showing signs of rapid decline (Hughes et al., 2003). The Global Status of Coral Reefs 2004 Report (Wilkinson, 2004) “predicts that 24% of the world's reefs are under imminent risk of collapse through human pressures; and a further 26% are under a longer term threat of collapse”. These large-scale changes within coral reef ecosystems are driving the need for ecologically relevant estimations of physiological parameters. Field survey techniques such as quadrats and belt transects using digital photo and video techniques are able to assess 100's m^2 of benthos (English et al., 1997; Rogers et al., 1994; Wilkinson and Hill, 2004), and with the rapidly increasing capacity for remote sensing tools (Mumby et al., 2004), data over entire reef systems can be obtained. Similarly, there many tools available for researches to assess coral reef parameters at the sub-colony scale but there are as yet none that allow the integration of measurements between the two data sets. This is a critical hindrance to developing knowledge on ecosystem function and habitat interaction at different scales.

The concept of a surface index (SI) introduced into marine biology by Dahl (1973) represents a potentially powerful tool to be able to apply measured parameters to more meaningful spatial scales. However, the methodology adopted by Dahl (1973) in developing these indices, reconstructing the target object from a series is simple geometric shapes. This resulted in an easily calculated SI, representing however, only a relatively crude approximation. Alcala and Vogt (1997) tested Dahl's theory on a range of coral growth morphologies and concluded that while the method of calculating the surface area from geometric shapes lacked reliable accuracy, the SI concept was a potentially useful methodology. Chancerelle (2000) took the SI concept a step further testing six species of coral, of differing morphology, for the existence of a SI relationship. Chancerelle (2000) and later Holmes et al. (in review) showed that a species specific linear relationship (i.e. SI) existed for each of the species tested, between the projected area of the coral and the actual three-dimensional surface area. These investigations have paved the way for the current study, whereby SI functions have been developed for gross coral growth morphologies. These SI functions provide a link between spatially large data sets such as belt transects and physiological measurements on coral surfaces.

2. Materials and methods

In selecting a methodology for measuring the actual three-dimensional surface area of corals, the issue of resolution was first considered. As outlined in Dahl (1973), there are several levels of complexity associated with coral reefs. At the level of the coral colony itself, there may be assumed to be two levels, the gross morphology and the complexity associated with corallite structure. This study has focussed on gross morphology as a potential link between spatially large data sets and small scale in-situ field measurements. Two methodologies were utilised (and compared): coating with paraffin wax (Stimson and Kinzie, 1991); and digital technology in the form of a handheld laser scanner at a resolution of 2.5 mm.

158 coral skeletons representing more than 25 genera up to 75 cm wide were sourced from collections at the Queensland Museum, and the University of Queensland. Although the majority of skeletons used were completely intact, some colonies with minor breakages were also included to broaden the applicability of the determined relationships as coral breakage is a natural phenomenon.

2.1. Surface Area Determination – Paraffin Wax

No discrimination was given to collection location or depth in selecting skeletons for analysis. The three-dimensional surface areas of colonies were calculated using a modified version of the paraffin wax method (Stimson and Kinzie, 1991). Skeletons at room temperature were weighed and dipped into a paraffin wax bath (Paraplast® Tissue Embedding Medium, Tyco Healthcare Group) maintained at 65 °C for 2 seconds. When removed from the bath they were rotated to optimise evenness of the coating. The initial coating seals the skeleton, reducing the influence of corallite rugosity and filling any cavities resulting from infaunal burrowers. The skeletons were re-weighed before and after being dipped for a second time in the paraffin wax.

Calibration objects of known surface area but of varying levels of complexity and surface texture (wood, plastic, coral, plastacene, $n=14$), were measured using the paraffin wax procedure. Using calibration objects of varying texture provides a test of whether surface roughness influences the conversion function (as would be identified by a poor correlation). The relationship between the weight of the second wax layer and the actual surface area of the objects is then used to calculate the three-dimensional surface area of the coral skeletons.

Regression analysis of the weight of the second wax coating to the three-dimensional surface area showed a strong correlation between the calibration objects and the weight of the second layer of paraffin wax deposited ($R^2>0.99$, $F_{1,12}=1744.96$, $P<0.0001$). The existence of a very strong correlation coefficient indicates that the initial surface properties of the objects being coated do not play any significant role in calculating the three-dimensional surface area of a dipped object from the weight of the second coating of paraffin. The average thickness of the initial layer of wax was 2 ± 0.5 mm (mean ± SE) while the second layer had an average thickness of 0.3 ± 0.01 mm.