Estimation of coral reef area volume and weight using a three dimensions (3D) photogrammetry

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Abstract. Current methods for measuring coral biomass remain limited, as they require direct data on coral weight and volume. Traditional techniques for estimating coral volume and weight are often invasive and inefficient. This study integrates underwater 3D photogrammetry based on the Structure-from-Motion (SfM) technique to develop predictive models for estimating coral volume and weight at Gili Labak Island, Sumenep. The analysis revealed that linear regression provided the highest accuracy for volume estimation ($y = 0.532x + 208.6$; $R^2 = 0.887$; RMSE = 148.7 ml), while the power regression performed best for weight estimation ($y = 1.0047x^{1.005}$; $R^2 = 0.906$; RMSE = 205.3 g). Application of these models to field plots produced realistic biomass estimates—8.6 tons in Plot A and 0.8 tons in Plot B—with corresponding carbon stocks of 97.5 kg C (4.9 kg C m^{-2}) and 9.1 kg C (0.5 kg C m^{-2}), respectively. These findings demonstrate that regression-calibrated 3D photogrammetry provides a non-destructive, accurate, and scalable approach for estimating coral biomass, offering significant relevance for coral reef conservation and management in data-limited regions.

1 Introduction

Traditional methods for measuring coral volume and weight are often invasive and inefficient (Courtney *et al*., 2007; Lange & Perry, 2020; Medellı *et al*., 2022; Herler & Dirnwöber, 2011; Reichert *et al*., 2016). The development of 3D photogrammetry technology offers a non-destructive approach that enables the reconstruction of three-dimensional coral models from underwater photographic imagery (Burns *et al*., 2015a). This technique has been applied in various studies to accurately assess coral structural complexity and volume (Irawan *et al*., 2023).

Gili Labak, a small island located in Sumenep, East Java, possesses significant coral reef potential (Lekatompessy *et al*., 2023). However, research on estimating coral volume and weight for conservation purposes remains limited. Therefore, this study aims to integrate 3D photogrammetry technology to develop a predictive model for estimating the volume and weight of coral colonies across three genera found in Gili Labak. The objective of this research is to establish a predictive model based on 3D photogrammetric imagery to estimate coral volume and weight for conservation management. The contribution of this study lies in the development of a model capable of representing coral structures in high detail and producing estimations that closely reflect actual conditions without requiring destructive physical measurements.

2 Research method

2.1 Coral sampling for model development

Coral samples were manually measured for weight and volume, after which each sample was photographed using 3D imaging to obtain three-dimensional visualizations. The reconstruction of underwater 3D imagery was performed using the Structure-from-Motion (SfM) approach, which has been proven to produce accurate models of coral colony structures (Burns *et al*., 2015b; Macedo *et al*., 2022; Greene *et al*., 2025; Herler & Dirnwöber, 2011; Raber & Schill, 2019; Ochhead & Nick Hedley, 2022; Hatcher *et al*., 2020). This photogrammetric technique reconstructs coral surfaces in detail to calculate parameters such as diameter, surface area, and volume (House *et al*., 2018). Image acquisition was conducted using an underwater camera from both planar and oblique angles with an overlap of 70–80% (Bythell & Pan, 2001).

The processing workflow included the following steps:
- Alignment of images based on invariant feature points,

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- Model calibration using underwater Ground Control Points (GCPs) (Bythell & Pan, 2001; Westoby *et al.*, 2012),
- Construction of a 3D mesh and calculation of colony volume (Kabiri *et al.*, 2020; de Oliveira *et al.*, 2021).

The 3D photo results were analyzed to obtain volume measurements. The 3D-derived volume data were then modeled using linear and nonlinear regression approaches to estimate coral volume and weight (Irawan *et al.*, 2023; Irawan & Muhsoni, 2023;Reichert *et al.*, 2016). The dependent variable (Y) represents the directly measured volume and weight, while the independent variable (X) corresponds to the volume derived from 3D photo analysis. The use of 3D photogrammetry and scanning methods allows for non-invasive measurements, preserving the coral's natural state and enabling continuous monitoring over time (Quigley, 2022; Lavy *et al.*, 2015)

2.2 Field data collection

In this stage, 3D photographic data of coral reefs were collected directly in the field through diving surveys. Underwater 3D photography was performed using planar and oblique overlapping techniques (SfM) to build 3D models of coral colonies (Burns *et al.*, 2015b; Cecarwati *et al.*, 2024), similar to the procedures used for coral samples. The resulting photographic data were analyzed using Agisoft Metashape and QGIS software to generate detailed 3D models.

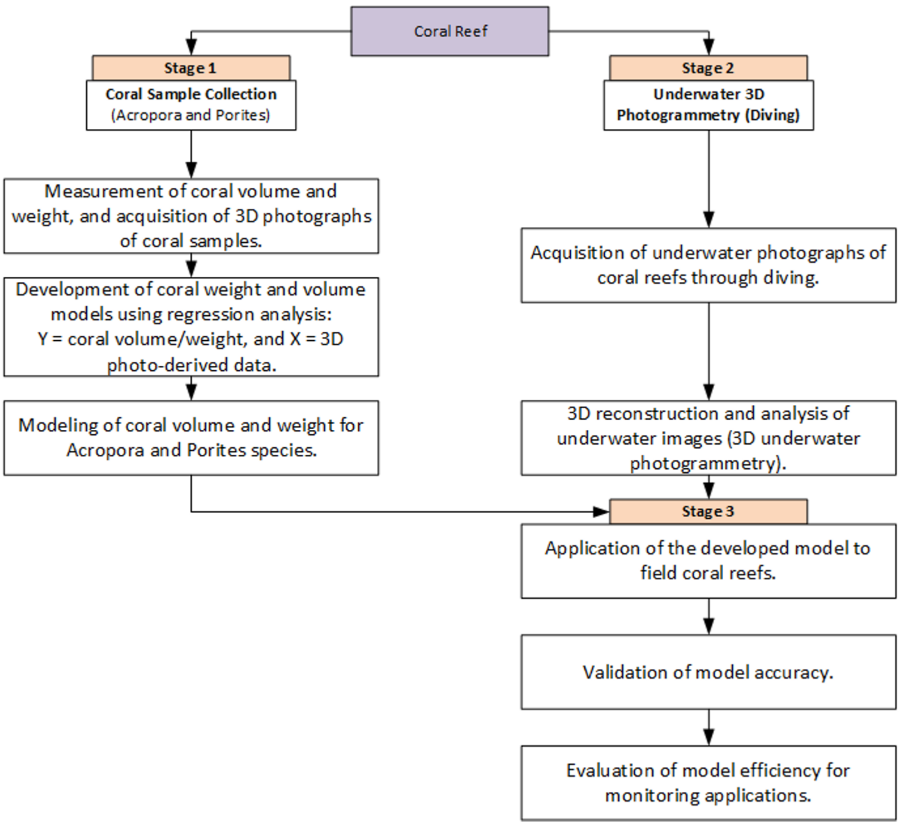

Fig. 1. Research flowchart.

3 Research result

The Underwater 3D Photogrammetry method is a coral reef survey approach based on the Structure-from-Motion (SfM) technique, enabling the construction of three-dimensional (3D) models of coral reef structures with high spatial precision. This method has become one of the most innovative techniques in coral ecosystem mapping, as it allows for the quantitative extraction of morphological, volumetric, rugosity, and habitat complexity information (Kornder *et al.*, 2021; Burns *et al.*, 2015a).

3.1 Field procedures

Image acquisition was performed using underwater digital cameras (DSLR, mirrorless, or action cameras equipped with waterproof housings) from multiple angles and along parallel transects. Photographs were taken with 70–80% lateral and frontal overlap to ensure the proper alignment of tie points during the 3D reconstruction process (Safuan *et al.*, 2015). This technique can be applied across various spatial scales, including microhabitats (small coral plots), mesohabitats (10–50 m transects), and even ecosystem-level mapping through mosaic imaging strategies (Zhong *et al.*, 2025).

3.2 3D volume and weight modeling

Equation models were developed to estimate 3D coral volumes based on several coral samples collected from the field. The modeling was conducted using both volume-based and weight-based approaches. The 3D volume obtained from image analysis using Agisoft Metashape 1.7.4 cannot be directly interpreted as the actual coral volume. This discrepancy arises because coral colonies possess unique morphological characteristics (Muhsoni & Abida, 2021), such as:

- Concave basal structures, which are often not captured in 3D models;
- Small internal cavities within the coral skeleton, which are not represented in photogrammetric reconstructions and thus lead to underestimation of volume.

To minimize these volumetric estimation errors, a conversion process using linear regression was applied (Muhsoni & Abida, 2021). Similarly, coral weight estimation was performed using linear and nonlinear regression models, where coral weight served as the dependent variable and the 3D-derived volume as the independent variable.

The resulting volume and weight estimation models are presented in Table 1, illustrating the predictive relationships between photogrammetric measurements and direct field observations.

Table 1. Regression models for estimating coral reef volume and weight.

No	Regression	Equations & coefficient of determination (R^2)	Accuracy Assessment		
			RMSE	% RMSE	% MAPI
Coral Reef Volume Estimation Model					
1	Linier	$y = 0.532x + 208.6$ $R^2 = 0.8869$ n = 32	148.7 ml	11,3	10,0
2	Power/geometry	$y = 0.3696x^{1.0738}$ $R^2 = 0.9202$ n = 32	246.4 ml	19.7	16.0
3	Polynomial	$y = -6E\text{-}05x^2 + 0.8645x - 111.62$ $R^2 = 0.9266$ n = 32	448.2 ml	35.8	19.2
Coral Reef Weight Estimation Model					
1	Linier	$y = 0.948x + 199.09$ $R^2 = 0.8299$ n = 37	227.6 gr	15.4	25.7
2	Power/geometry	$y = 1.0047x^{1.005}$ $R^2 = 0.9056$ n = 37	205.3 gr	13.9	18.0
3	Polynomial	$y = -6E\text{-}05x^2 + 1.2x - 9.1481$ $R^2 = 0.8332$ n = 37	207.0 gr	14.0	14.3

To validate the best-fitting regression equation for estimating coral reef volume and weight, an accuracy assessment was conducted. This evaluation aimed to determine the magnitude of estimation errors using Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE) tests.

The RMSE test compared the estimated coral volumes derived from the 3D photogrammetric regression model with the directly measured field data. The results demonstrated that the best regression equation for estimating coral volume was the linear regression model expressed as $y = 0.532x + 208.6$ This model produced an RMSE value of 148.7 mL, an RMSE percentage of 11.3%, and a MAPE value of 10%. These results indicate a significant improvement over the previous study by Muhsoni & Abida (2021), which reported an RMSE of 139.7 mL and an RMSE percentage of 20.1% using only 11 samples.

3.3 Application of the model to a broader area-ploat A

For Plot A (Fig. 2), data acquisition was conducted as follows: 497 photographs, average camera height 1.29 m, ground sampling distance 0.33 mm/pixel, mapped area 31.6 m². The camera used was an Olympus TG-6 (4.5 mm) with an image resolution of 4000 × 3000 pixels and a pixel size of 1.5 × 1.5 µm. Reconstruction accuracy achieved X error = 11.12 cm, Y error = 12.86 cm, Z error = 10.85 cm, with a total error = 20.17 cm. Restricting coral coverage to 2 × 10 m², the 3D photogrammetric volume computed in Agisoft Metashape was 7,898,000 cm³. Applying the linear regression volume-correction model $(y = 0.532x + 208.6)$yielded an estimated true volume of 4,201,945 cm³. Converting volume to biomass (weight) using the power/geometric model $(y = 1.0047x^{1.005})$resulted in 8,590,949 g (8.59 t) of coral. Assuming an average organic carbon content of 1.135%, the estimated coral carbon stock for Plot A is 97,491 g (97.49 kg) per 2 × 10 m², equivalent to 4.9 kg m^{-2}.

3.4 Application of the model to a broader area-ploat B

For Plot B (Fig. 3), data acquisition comprised 680 photographs, an average camera height of 87.9 cm, ground sampling distance 0.211 mm/pixel, and a mapped area of 35.3 m². The camera specifications were identical to Plot A: Olympus TG-6 (4.5 mm), image resolution 4000 × 3000 pixels, pixel size 1.5 × 1.5 µm. Reconstruction accuracy achieved X error = 4.87 cm, Y error = 1.73 cm, Z error = 3.58 cm, with a total error = 6.29 cm.

Restricting coral coverage to 2 × 10 m², the volume estimated using the linear regression volume-correction model $(y = 0.532x + 208.6)$was 396,406 cm³. Converting this volume to biomass (weight) using the power/geometric regression $(y = 1.0047x^{1.005})$yielded 800,565 g (0.8 t) of coral. Assuming an average organic carbon content of 1.135%, the estimated coral carbon stock for Plot B is 9,084 g (≈9 kg) per 2 × 10 m², equivalent to 0.5 kg m^{-2}.

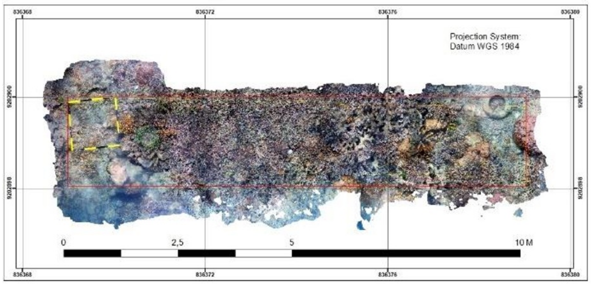

Fig. 2. Three-dimensional coral reef map derived from plot A analysis.

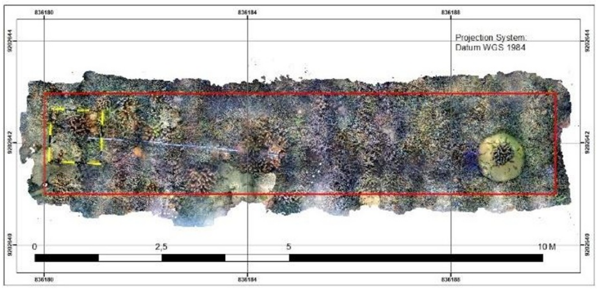

Fig. 3. Three-dimensional coral reef map derived from plot B analysis.

4 Conclusion

This study demonstrates that underwater 3D photogrammetry, when calibrated with regression models, provides a non-destructive and efficient approach for estimating coral volume and weight. Because raw mesh volumes often fail to represent true conditions—due to concave bases and fine internal cavities—conversion via regression equations is required to minimize bias. Among the tested models, linear regression yielded the highest accuracy for volume estimation ($y = 0.532x + 208.6$; $R^2 = 0.887$; RMSE = 148,7 ml; %RMSE = 11,3; MAPI = 10,0), whereas the power regression performed best for predicting weight (y = 1.0047x^1.005; $R^2 = 0.906$; RMSE = 205,3 g; %RMSE = 13,9; MAPI = 18,0). Field-scale application of the models at Gili Labak produced realistic biomass estimates: (Plot A: volume $4{,}20\times10^6$ cm³ ≈ 4,2 m³ and weight $8{,}59\times10^6$ g ≈ 8,6 ton; Plot B: volume $3{,}96\times10^5$ cm³ ≈ 0,40 m³ and weight $8{,}01\times10^5$ g ≈ 0,8 ton). Estimated carbon stocks were 97,5 kg C in Plot A (4,9 kg C m^{-2}) and 9,1 kg C in Plot B (0,5 kg C m^{-2}).

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