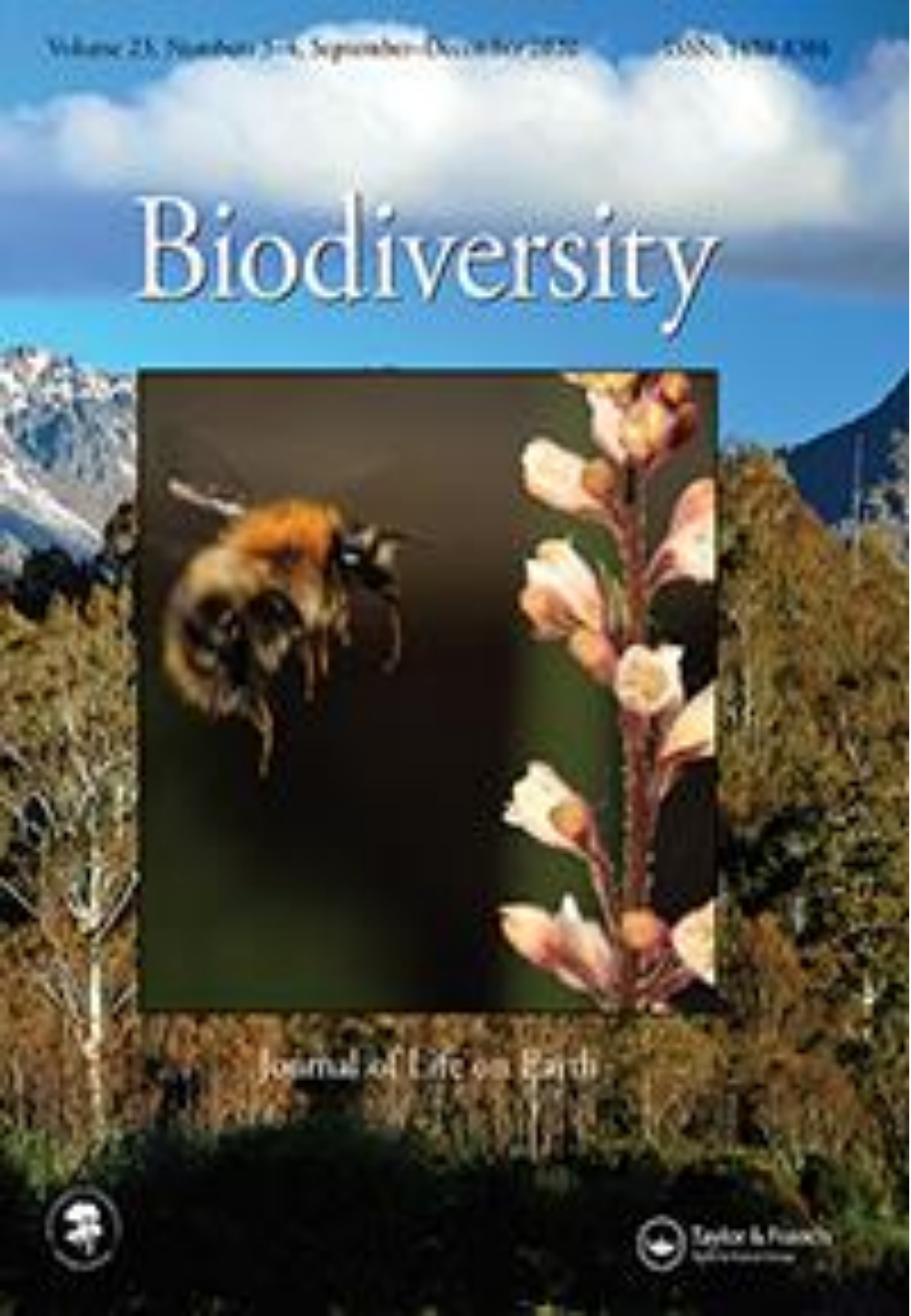
Volume 23, Number 3–4, September–December 2022 ISSN [illegible]

Biodiversity

Journal of Life on Earth



Taylor & Francis

KORESPONDENSI

Nama Jurnal : Biodiversity

Judul Artikel : Three-dimensional (3D) modelling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

No.	Proses	Waktu
1.	Submit manuskrip	31 Desember 2022
2.	Revisi dari Editor Jurnal	4 Januari 2023
3.	Revisi manuskrip	7 Januari 2023
4.	Under review oleh reviewer jurnal	7 Februari 2023
5.	Reminder dari editor jurnal	8 Februari 2023
6.	Revisi manuskrip dan re-submit manuskrip revisi	20 Februari 2023
7.	Reminder dari editor jurnal	22 Februari 2023
8.	Accepted jurnal	23 Februari 2023
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12.	Revisi artikel dan re-submit	12 Maret 2023
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15.	Revisi artikel dan re-submit	20 Maret 2023
16.	AcceptedAuthorPublishingAgreement	20 Maret 2023
17.	Publish artikel di jurnal	23 Maret 2023

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ACTION	STATUS	ID	TITLE	SUBMITTED	DECISIONED
	ME: Trueman, Rebecca • Accept (20-Feb-2023) view decision letter Contact Journal	TBID-2023-0005.R1	Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia View Submission	19-Feb-2023	20-Feb-2023
a revision has been submitted (TBID-2023-0005.R1)	ME: Trueman, Rebecca • Minor Revision (07-Feb-2023)	TBID-2023-0005	Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura,	11-Jan-2023	07-Feb-2023

ACTION	STATUS	ID	TITLE	SUBMITTED	DECISIONED
	• a revision has been submitted view decision letter Contact Journal		East Java, Indonesia View Submission		
	ME: Trueman, Rebecca • Reject - Inappropriate view decision letter Contact Journal	TBID-2022-0092	Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia View Submission	31-Dec-2022	03-Jan-2023

SMART UNIVERSITY

akhmad taufiq mukti <akhmad-t-m@fpk.unair.ac.id>

Biodiversity - Manuscript ID TBID-2022-0092 has been submitted online

1 message

Biodiversity <onbehalfof@manuscriptcentral.com> Sun, Jan 1, 2023 at 2:02 AM
Reply-To: rtrueman@biodiversityconservancy.org
To: akhmad-t-m@fpk.unair.ac.id, atm.mlg@gmail.com

31-Dec-2022

Dear Dr Mukti:

Your manuscript entitled "Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia" has been successfully submitted online and is presently being given full consideration for publication in Biodiversity.

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akhmad taufiq mukti <akhmad-t-m@fpk.unair.ac.id>

Coral paper

2 messages

Rebecca Trueman <rtrueman@biodiversityconservancy.org> Wed, Jan 4, 2023 at 4:21 AM
To: "akhmad-t-m@fpk.unair.ac.id" <akhmad-t-m@fpk.unair.ac.id>, "atm.mlg@gmail.com" <atm.mlg@gmail.com>

Dear Akhmad,
Thank you for the submission of your paper. It is interesting but before I could send for peer review it requires significant editing for clarity. Even the abstract is confusing. Below is an example of the type of clarity that would be required. I am going to reject the paper, but once edits are made, I encourage you to resubmit.

This study aimed to non-destructively measure the weight of massive (live) corals through ~~massive (dead) corals using~~ the use of three-dimensional (3D) modeling. The 3D models were constructed using volumes and ~~by calculating the estimated~~ weight of massive (dead~~life~~) corals. The study was conducted through photographs, 3D analysis, and weighing of 32 massive (dead) coral samples. Volume and weight were modeled using linear and non-linear regressions and their accuracy was tested using root mean square error (RMSE) and mean absolute percentage error (MAPE). The results showed that regression equation of volume was y=0.964x+314.470, R^2=0.912 with RMSE, %RMSE, and MAPE of 284.50 g, 20.50%, and 27.43%, respectively. Polynomial equation was y=-0.001x^2+1.235x + 49.448, R^2=0.916 with RMSE, %RMSE, and MAPE of 251.20 g, 18.10%, and 19.17%, respectively, while geometric equation was y=2.451$x^{0.898}$, R^2=0.915 with RMSE, %RMSE, and MAPE of 354.30 g, 25.50%, and 24.77%, respectively. Linear regression obtained an average

Trueman, Rebecca 4 minutes ago
Much too detailed for an abstract- you need to summarize results in a way that readers can understand.

All the best, Rebecca

Rebecca Trueman PhD
Managing Editor of Biodiversity
rtrueman@biodiversityconservancy.org

akhmad taufiq mukti <akhmad-t-m@fpk.unair.ac.id> Wed, Jan 4, 2023 at 11:58 AM
To: Dedi Irawan <dedi.awan-2020@fpk.unair.ac.id>

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2 attachments

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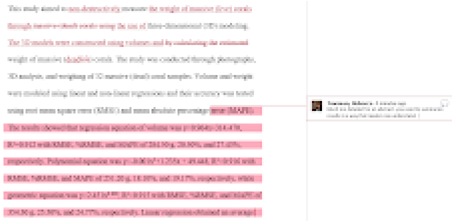

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Reply-To: rtrueman@biodiversityconservancy.org
To: akhmad-t-m@fpk.unair.ac.id, atm.mlg@gmail.com

03-Jan-2023

Dear Dr Mukti

I regret to inform you that the editorial team does not feel your manuscript is suitable for publication in Biodiversity at this time. The main reason for this decision is due to the standard of English language within your manuscript. Please can I take this opportunity to advise you to do a full review of your manuscript.

You are of course now free to submit the paper elsewhere or resubmit to us once the language is corrected should you choose to do so.

Sincerely,
Rebecca Trueman
Managing Editor, Biodiversity

akhmad taufiq mukti <akhmad-t-m@fpk.unair.ac.id> Wed, Jan 4, 2023 at 11:58 AM
To: Dedi Irawan <dedi.awan-2020@fpk.unair.ac.id>

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1 message

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11-Jan-2023

Dear Dr Mukti:

Your manuscript entitled "Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia" has been successfully submitted online and is presently being given full consideration for publication in Biodiversity.

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Biodiversity <onbehalfof@manuscriptcentral.com> Tue, Feb 7, 2023 at 10:34 PM
Reply-To: rtrueman@biodiversityconservancy.org
To: akhmad-t-m@fpk.unair.ac.id, atm.mlg@gmail.com
Cc: rtrueman@biodiversityconservancy.org

07-Feb-2023

Dear Dr Mukti:

Your manuscript entitled "Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia", which you submitted to Biodiversity, has been reviewed. The reviewer comments are included at the bottom of this letter.

The reviews are in general favourable and suggest that, subject to minor revisions, your paper could be suitable for publication. Please consider these suggestions, and I look forward to receiving your revision.

When you revise your manuscript please highlight the changes you make in the manuscript by using the track changes mode in MS Word or by using bold or coloured text.

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Because we are trying to facilitate timely publication of manuscripts submitted to Biodiversity, your revised manuscript should be uploaded by 21-Feb-2023. If it is not possible for you to submit your revision by this date, we may have to consider your paper as a new submission.

Once again, thank you for submitting your manuscript to Biodiversity and I look forward to receiving your revision.

Sincerely,
Rebecca Trueman
Managing Editor, Biodiversity Journal

Reviewer(s)' Comments to Author:
Please see the attached file.

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Biodiversity <onbehalfof@manuscriptcentral.com> Tue, Feb 7, 2023 at 10:36 PM

Reply-To: aitkense@biodiversityconservancy.org
To: akhmad-t-m@fpk.unair.ac.id, atm.mlg@gmail.com

07-Feb-2023

Dear Dr Mukti,

Thank you for resubmitting your paper to Biodiversity.

I am delighted to inform you that your paper has now been accepted by the Biodiversity, subject to revision along the lines suggested below, and the reviewer comments at the end of this letter.

I would be grateful if you could now provide a final paper following (Journal) guidelines, with a Title page containing authors affiliation and e-mail address (page 1), followed by Abstract and Key Words (page 2), and full text, all in the same document. Only tables and figures are to be included as a separate document.

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IMPORTANT: Your original files are available to you when you upload your revised manuscript. Please delete any redundant files before completing the submission.

Because we aim for the timely publication of manuscripts submitted to Biodiversity, please upload your revised manuscript as soon as possible and before 21-Feb-2023.

Once again, thank you for submitting your manuscript to Biodiversity and I look forward to receiving your revision.

Sincerely,
Stephen Aitken
Managing Editor, Biodiversity Journal
aitkense@biodiversityconservancy.org, aitkense@gmail.com

Reviewer(s)' Comments to Author:

Reviewer: 1

Comments to the Author
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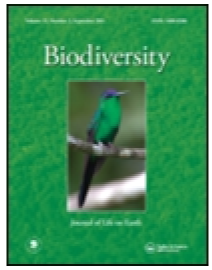

Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

Journal:	*Biodiversity*
Manuscript ID	TBID-2023-0005
Manuscript Type:	Article
Keywords:	Coral reef, Gili Labak Island, three-dimensional modeling, volume, weight

Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

ABSTRACT

This study aimed to non-destructively measure the weight of massive (live) corals through three-dimensional (3D) modeling. The 3D models were constructed using the volumes and weight of massive (dead) corals. The study was conducted through photographs, 3D analysis, and weighing 32 massive (dead) coral samples. Volume and weight were modeled using linear and non-linear regressions, and their accuracy was tested using root mean square error (RMSE) and mean absolute percentage error (MAPE). This study showed that the weight of massive (live) corals could be measured using a 3D model of the massive (dead) coral's volume and the weight mainly through regression, polynomial, and geometric equations. The power/geometric equation is a more suitable approach to the actual value of coral weight. Linear regression obtained an average weight of 6.13 kg per plot. 3D modeling can be widely applied to measure the massive corals in the deep sea.

Keywords: Coral reef; Gili Labak Island; three-dimensional modeling; volume; weight

Introduction

The preservation of coral reef ecosystems is critical because many people in the twenty-first century will rely on these resources for food production, coastal protection, and the survival of their ecosystems (Kleypas et al. 2021). Coral reefs are among the most diverse and threatened ecosystems (Hoegh-Guldberg et al. 2019). Therefore, Monitoring its responses to various threats and disturbances is critical for management and conservation. Understanding the best methods for measuring changes in corals, ecosystems, and their functions is a challenge. An emerging method for exploring colony-scale growth patterns employs underwater photogrammetry to create digital models of coral colonies (Lange and Perry 2020). Acoustic methods are currently widely used to detect the presence of underwater objects. Their systems work exceptionally well.

Developing methodologies that allow the incorporation of three-dimensional (3D) metrics into coral reef monitoring is critical. One of the most commonly used metrics for assessing reef health is the proportion of live coral cover on reefs (Leujak and Ormond 2007). It is used as a proxy for calculating coral reef biomass and grows on the capabilities of most techniques used to evaluate linear or horizontal planar estimates. However, 2D alone is insufficient to estimate coral reef cover (Bamford and Forrester 2003), whereas 3D coral reefs provide valuable information on health (Dickens et al. 2011). The 3D surface and volume provide more accurate coral abundance statistics and allow for more accurate mapping of coral reef changes.

Manta tow, line intercept transect (LIT), point intercept transect (PIT), belt transect (BT), and quadratic transect are standard research methods in coral reefs, depending on the purpose (QT). The 3D modeling method is an advancement and modification of the underwater photo transect (UPT) method, which uses 3D photographs to identify coral species. As a result, 3D surface area and volume can provide more accurate metrics of coral abundance information and allow for more accurate capture of changes in coral reefs. This modeling is the most effective method for assessing coral reef damage and estimating carbon stocks. Comparison, photogrammetry, and 3D models offer a quick, simple, low-cost, and non-invasive method (Lange and Perry 2020). This study is a cost-effective and non-invasive method for accurate geometrical measurements of corals. Because it is impossible to obtain photos of all coral surfaces and know the estimated weight of corals using a 3D approach, accuracy is highly dependent on the complexity of the coral reef. This study aimed to non-destructively measure the weight of massive (live) corals through 3D modeling.

Materials and methods

Research location

This study was conducted at 8 to 12 m on Gili Labak Island, Talango Sub-District, Sumenep Regency, Madura, East Java, Indonesia. The map of the study location is shown in Figure 1.

Sampling

A 3D model was created using 30 colonies of massive dead corals that were weighed to determine their weight and photographed for analysis in the Agisoft Methasape Professional (AMP) software. The volume and weight results were used to find the linear and regression non-linear equations. Second, 30 coral samples were used for the accuracy test, and volume was measured in the pond using an Olympus TG-6 camera on a transect of 30 cm × 30 cm and in the field using the frame 50 cm × 50 cm for live coral. (Figueira et al. 2015).

3D measurement of massive corals

AMP software was also used to analyze the results of coral photos. First, the image quality of underwater photos was estimated using the image's sharpness, exposure, focus, resolution, and depth of field. The camera and build dense cloud (BDC) were then synced with the software and scaled with a scale. Third, a dense point cloud was created using depth information from each camera and a densification algorithm. Fourth, 3D nets were built. Create texture (optional), but performing 3D measurement and analysis is not required. Planar projections by orthographic views were used to isolate a "cleaning" coral colony model from other reconstructed elements such as reef foundations, and AMP editing oriented all models. Exported models were used for quantitative analysis and volume calculations (Kabiri et al. 2020; de Oliveira et al. 2021).

Before taking the 3D photo in the pond, the coral was weighed. The data was collected to create a model using linear and non-linear regression. Following that, 32 massive corals from the second sample were weighed for root mean square error (RMSE) and mean absolute percentage error (MAPE) tests.

Underwater camera photo

Coral colonies were photographed from every angle possible, including above and below. As shown in Figure 2, the camera was positioned at each object's angle (Burns et al. 2015). The 3D volume was measured by diving to a depth of 8 m and collecting 32 coral colonies. A schematic of the camera position is used to generate 3D images, as shown in Figure 2 (Ahmad et al. 2020).

Massive corals were photographed in the pond using a 30 cm × 30 cm transect, while coral reefs were photographed in the field using a 50 cm × 50 cm transect (Ahmad et al. 2020). Continuous underwater photography from oblique planes and angles captured the entire colony surface (Figure 2), with 70 to 80% overlap (Bythell and Pan 2001; Burns et al., 2019). All photos were uploaded to the AMP software, and the camera was calibrated using metadata-derived focus information. Furthermore, the photos were aligned using an algorithm capable of detecting invariant features that overlap between consecutive photos. A geometric projection matrix was created using invariant features and the position, and the camera orientation for each photograph was determined according to Westoby et al. (2012). Extrinsic parameters calculated during the photo-alignment process were combined with intrinsic and focal parameters obtained from the metadata to create the 3D geometry from 2D images (Stal et al. 2012). Bookmarks were used as a manual for all ground control points (GCP), and the location of each marker in all photos containing the GCP was reviewed and corrected. Values of x, y, and z for each GCP were entered into the software to optimize alignment and ensure the resulting model's accurate interior and exterior orientation.

The pattern of relationships between independent and dependent variables on the 3D weight and volume of coral reefs was determined using regression analysis (Scott et al. 1991). Regression analysis was divided into linear and non-linear regressions based on the relationship pattern. When the variables have power/geometric, the model is called a non-linear regression. When a non-linear regression model in parameters is differentiable, the result is always a function in parameters, as stated. The non-linear regression in parameters was calculated according to Scott et al. (1991). Statistical analysis was performed on three regression and non-linear regression equation models, linear, polynomial, and power/geometric, based on 3D volume and weight photographs of massive (dead) corals.

Root mean square error (RMSE) test.

An accuracy test was carried out to determine the best equation for estimating the volume and weight of coral reefs. Using the RMSE test, an accuracy test was used to determine the error value of the regression equation. Then, 3D volume photographs were compared to 3D weight photographs. The RMSE equation was used:

$$\text{MSE} = \sqrt{\frac{i}{n}\sum_{i=1}^{n}(x_1 - y_1)^2}$$

$$\text{RMSE}(\%) = \frac{RMSE}{\acute{Y}} \times 100$$

Note: MSE = mean square error, RMSE = root mean square error, x_1 = 3D measurement result value, y_1 = 3D value prediction, and Ý = average 3D measurement results (Suprayogi et al. 2014; Gurchiek et al. 2017)

Mean absolute percentage error (MAPE) test

MAPE was used to evaluate the estimation of the results and determine the accuracy of the estimated number and the realization rate. The following formula was used to calculate the value:

$$\text{MAPE}(\%) = \frac{\sum_{t=1}^{n}\frac{[A_t - F_t]}{At}}{n} \times 100$$

Note: MAPE = mean absolute percentage error, Ft = estimated value at time t, At = actual value at time t, and n = total data (t = 1, 2, .., n).

The MAPE test model's accuracy was measured using three criteria: very accurate (MAPE<5%), accurate (5%<MAPE<10%), and inaccurate (MAPE>10%) (Nabillah and Ranggadara 2020).

Data analysis

3D photos were taken in a small pond with 30 colonies to find linear and non-linear regression models, 30 colonies for accuracy tests, and 32 samples of massive coral reef colonies for comparison (Fukunaga and Burns 2020). The digital elevation model (DEM) is a raster grid that references the subject surface's starting point. This modeling allows for the removal of objects from the surface, resulting in a 3D model with a smooth surface. If the DEM image does not appear during analysis, the volume results will not be displayed, and the analysis cannot be continued in the AMP software. The average number of photos analyzed in 3D for each coral colony was 93 to 98. The photos were then analyzed in software (Lange and Perry 2020) using AMP software (Kabiri et al. 2020; de Oliveira et al., 2021).

Results

Develop a 3D volume model of dead coral samples collected in the field. The use of dead coral samples to avoid causing harm to the coral ecosystem at the study site. Experiments with a frame binding point of 30 cm × 30 cm yielded photographs of dead coral samples. The number was indicated as a binding point in the corner of the frame; the binding point's purpose is to serve as a GCP for 3D photo analysis. The results of the dead coral colonies analysis are presented in Figure 3.

The results of underwater analysis of 3-dimensional images captured with AMP software on 30 massive (dead) coral colonies in a pond yield 3D modeling volumes on coral samples, with images captured of the entire coral surface. Each coral sample contains an average of 102 photographs. Table 1 shows the results of the RMSE control point analysis on the 3D photo analysis of corals in the pond.

The photos were analyzed in 3D using the AMP 1.7.4 software, and the RMSE control point value was calculated. Based on analysis, the 3D photo error in the water (small pond) is less than 1 mm. The 3D photo analysis yielded an average RMSE of coral reefs for photos in small ponds with an average of 102 photos, an average X error of 0.29206 mm, Y error of 0.50167 mm, Z error of 0.34566 mm, XY error of 0.59070, and a total error of 0.72119 mm. The water's influence can affect the camera to distort.

Coral samples were also weighed to calculate the mass of massive corals. All coral samples from the 3D photo volume and the weight of dead corals were used to obtain a model for the estimated live coral weight. The volume of 3D photos and the weight of corals in (Table 1) are used to construct a model using linear and non-linear regression equation approaches. Table 2 displays the results of linear and non-linear regression analysis of weight and volume using AMP software.

Table 2 showed that the model with the best accuracy of power/geometric resulted in $y = 2.451x^{0.898}$, $R^2 = 0.916$ with RMSE test of 251.20 g, %RMSE of 18.10%, and MAPE of 19.17%, while linear regression resulted in $y = 0.964x + 314.470$, $R^2 = 0.912$, RMSE of 284.50 g, %RMSE of 20.50%, and MAPE of 27.43%. Meanwhile, the polynomial resulted in $y = 0.001x^2 + 1.235x + 49.448$ $R^2 = 0.915$ with RMSE test of 354.30 g, %RMSE of 25.5%, and MAPE of 20.0%. Based on its orthographic projections, the coral colony orientation is utilized to calculate volume. On the other hand, growth orientation is influenced by environmental factors such as habitat complexity, slope, light, and plane, potentially leading to estimation bias.

The volume of the coral reef could not be directly considered in the 3D photo analysis using AMP software due to the coral reef has a complex shape and concave bottom with small cavities. Calculating the volume of a 3D photo model is usually invisible and legible. As a result, a conversion is required to minimize errors when using a regression approach. The power/geometric conversion of the model from the initial data to the linear regression equation model is y = 2.451x0.898, R2= 0.916 with RMSE test of 251.20 g, %RMSE of 18.10%, and MAPE of 19.17%.

Data on coral reef

The results of the analysis of live coral colonies on Gili Labak Island can be seen in Figure 4. The modeling application and field data collection were tested on Gili Labak Island. Photos were taken by diving at depths ranging from 8 to 12 m with a sample of 32 coral colonies. The iron frame used is 50 cm × 50 cm or 2500 cm^2, with a mark on each corner of the frame serving as a binding point for the photo and making analysis more accessible in the AMP software. The results of the 3D analysis are seen in Table 3.

The model conversion from the initial data using the power/geometric equation model was $y = 2.451x^{0.898}$ with $R^2 = 0.916$. In Gili Labak Island, the average weight of coral volume produced is 6.13 kg per plot, and the total coral volume for the 32 plots is 169.92 kg, with a maximum value of 32.92 kg per plot and a minimum value of 0.04 kg per plot.

Discussion

The diversification of new methods in coral reef research is increasing. In this study, a new method was used to assist other examiners who do not have direct experience in identifying coral reefs in the sea, allowing novices to process the data and identify coral reefs on land without direct identification in the field. One advantage of the 3D method used in this study is the ability to obtain more controlled and verifiable data and data on the volume of coral reefs that were never obtained using previous methods. This study uses DEM results from AMP software to determine the volume of massive coral colonies and then models massive coral weight in Gili Labak Island, Sumenep, Madura. 3D modeling is the most effective data presentation method for describing coral reef damage. Acoustic methods are now commonly used to detect the presence of underwater objects. This system is beneficial for exploring the underwater environment (Kornder et al. 2021).

The emerging method of developing digital models of coral colonies using underwater photogrammetry provides a new and non-invasive way to examine colony-scale growth patterns and fill existing knowledge gaps (Lange and Perry 2020). The main difficulty in coral reef ecology is estimating the abundance and composition of communities living in such complex ecosystems (Kornder et al. 2021). This study used technological advances to identify volumes in massive coral colonies using a 3D model. The advancement of photogrammetric technology has created a viable and practical method for exploring coral reefs (House et al. 2018). The structural parameters of reef surfaces and organisms have been shown to have relatively high accuracy when using photogrammetry in combination with underwater photogrammetry (Veal et al. 2010; Bryson et al. 2017).

Testing accuracy and precision are critical in any research, including underwater photogrammetry of coral reefs. The accuracy and precision of the geometry obtained from the massive coral reef's 3D model were tested in this study. As a result, 3D measurement is an accurate quantitative study of the physiology and various sizes of coral colonies, and it can be done in situ. This technique could also be used to measure morphometrics of branching species, such as branch spacing, density, branch length, and branch angle. The 3D method precisely measures architectural complexity, topography, rugosity, volume, and other critical structural properties in ecosystems (Burns et al. 2015). This method reconstructs the 3D structure of coral reefs and habitat-forming organisms at high resolution and accuracy by using a series of overlapping images taken from multiple perspectives (Bryson et al. 2017).

This study also included the RMSE test results, which had a value of 18.10% and a MAPE of 19.17%, whereas Hatcher et al. (2020) produced a relative RMSE of 0.013%. This result produced a higher value when compared to Figueira et al. (2015), who obtained 10% results from bottle coral measurements.

Photogrammetry was initially developed and applied in terrestrial settings, but it has since become a valuable tool for creating 3D models of bathymetry and underwater habitats. Because complete recordings of all surfaces are not possible, complex corals could not be observed adequately with this model. This is a non-invasive method for obtaining precise geometric measurements of corals and other irregular underwater objects (Bythell and Pan 2001).

Conclusions

The massive corals in the deep sea can be identified and measured using 3D modeling. This study will continue to calculate the carbon stock of coral reefs in the future. This method is a non-invasive, cost-effective, and timesaving approach to obtaining accurate coral geometric measurements. Due to the difficulty in obtaining complete photos of all surfaces, accuracy is highly dependent on the complexity of the coral reef.

Acknowledgments

The authors would like to thank the Directorate of Research, Technology, and Community Services (DRTPM), General Directorate of Higher Education, Research, and Technology, Ministry of Education, Culture, Research, and Technology, Republic of Indonesia. The authors would also like to thank the editor, reviewers, and proofreaders for the comments, corrections, and suggestions to improve this article.

Author contributions

DI conceptualized, collected the materials, performed the experiment, measured parameters, analyzed the data, and prepared the manuscript draft; ATM conceptualized, designed, and analyzed the data, edited and corrected the final manuscript; SA corrected English Grammarly and proofread the manuscript draft; FFM designed and corrected the manuscript draft. All authors read and approved the final manuscript.

Disclosure statement

The authors declare that they have no conflict of interest.

Funding information

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Table 1. RMSE control points on the results of 3D photo analysis in a small pond.

No coral	Number of photo	RMSE				
		X error (mm)	Y error (mm)	Z error (mm)	XY error (mm)	Total (mm)
1	97	0.55387	1.13955	0.77888	1.26703	1.48728
2	100	0.27418	0.18195	0.04357	0.32906	0.33193
3	96	0.86821	0.86821	2.64072	1.18693	2.89520
4	94	0.44546	0.40574	0.48895	0.60255	0.77597
5	102	0.16377	0.31121	0.01835	0.35167	0.35215
6	95	0.23989	0.26469	0.32463	0.35722	0.48270
7	89	0.01553	0.23047	0.15672	0.23099	0.27913
8	96	0.31492	0.28618	0.41279	0.42553	0.59285
9	110	0.26506	0.24065	0.15519	0.35801	0.39020
10	82	0.19772	0.57799	0.20527	0.60183	0.63587
11	89	0.06381	0.21831	0.12998	0.22744	0.26196
12	115	0.26025	0.42471	0.20647	0.49811	0.53921
13	114	0.26427	0.30750	0.20589	0.40546	0.45474
14	114	0.10470	0.33880	0.18488	0.35461	0.39992
15	95	0.15410	0.33145	0.23749	0.36552	0.43590
16	100	0.10025	0.36274	0.18387	0.37634	0.41886
17	102	0.05425	0.34436	0.16343	0.34861	0.38502
18	104	0.11650	0.13726	0.14757	0.18004	0.23279
19	93	0.30765	0.43068	0.06607	0.52928	0.53339
20	100	0.26892	0.42773	0.26986	0.50525	0.57280
21	110	0.08382	0.15316	0.26245	0.17459	0.31522

22	113	0.08055	0.18929	0.28779	0.20571	0.35375
23	114	0.16094	0.20679	0.04977	0.26204	0.26673
24	111	2.18783	5.24739	0.98116	5.68522	5.76926
25	110	0.14644	0.34430	0.68882	0.37415	0.52542
26	119	0.51075	0.23892	0.66404	0.56387	0.87115
27	94	0.10643	0.17073	0.18373	0.20119	0.27246
28	108	0.08465	0.21065	0.01163	0.22703	0.22733
29	101	0.07523	0.20130	0.13604	0.21490	0.25434
30	103	0.17461	0.25764	0.08381	0.31109	0.32218
Average	102	0.29206	0.50167	0.34566	0.59070	0.72119

Table 2. The volume of coral reefs from 3D photo analysis by weight.

Analysis	Massive coral reefs	Test data
Linear	$y = 0.964x + 314.470$	RMSE = 284.50 g
	$R^2 = 0.912$	%RMSE = 20.50%
		MAPE = 27.43%
Polynomial	$y = 0.001x^2 + 1.235x + 49.448$	RMSE = 354.30 g
	$R^2 = 0.915$	%RMSE = 25.50%
		MAPE = 20.00%
Power/geometric	$y = 2.451x^{0.898}$	RMSE = 251.20 g
	$R^2 = 0.916$	%RMSE = 18.10%
		MAPE = 19.17%

Table 3. The volume of 3D photos produced by AMP software and volume of coral conversion using a power/geometric model.

No.	The volume of 3D photo analysis (cm^3)	Coral weight estimation using power/geometric model (g)	Genus of coral
1	2951	3191.71	*Favia*
2	3173	3406.42	*Favites*
3	6045	6075.19	*Pavona*
4	39727	32924.42	*Favia*
5	26236	22687.22	*Leptoseris*
6	5402	5491.86	*Favia*
7	5125	5238.42	*Coscinaraea*
8	8601	8337.39	*Leptoria*
9	1825	2073.42	*Favia*
10	2564	2813.35	*Caulastrea*
11	2093	2344.78	*Caulastrea*
12	3937	4134.27	*Pavona*
13	13706	12666.88	*Montastrea*
14	1703	1948.57	*Montastrea*
15	23181	20301.18	*Favites*
16	4388	4556.98	*Favia*
17	2223	2475.09	*Psammocora*
18	2983	3222.76	*Goniastrea*
19	4112	4298.86	*Favia*
20	384	511.77	*Montastrea*
21	10421	9904.99	*Psammocora*

22	4016	4208.66	*Psammocora*
23	7715	7562.26	*Coscinaraea*
24	21	37.69	*Leptoseris*
25	7036	6962.07	*Psammocora*
26	14529	13347.55	*Psammocora*
27	226	318.00	*Euphyllia*
28	969	1174.64	*Psammocora*
29	471	614.73	*Montastrea*
30	255	354.40	*Porites*
31	253	351.90	*Porites*
32	2509	2759.12	*Favia*

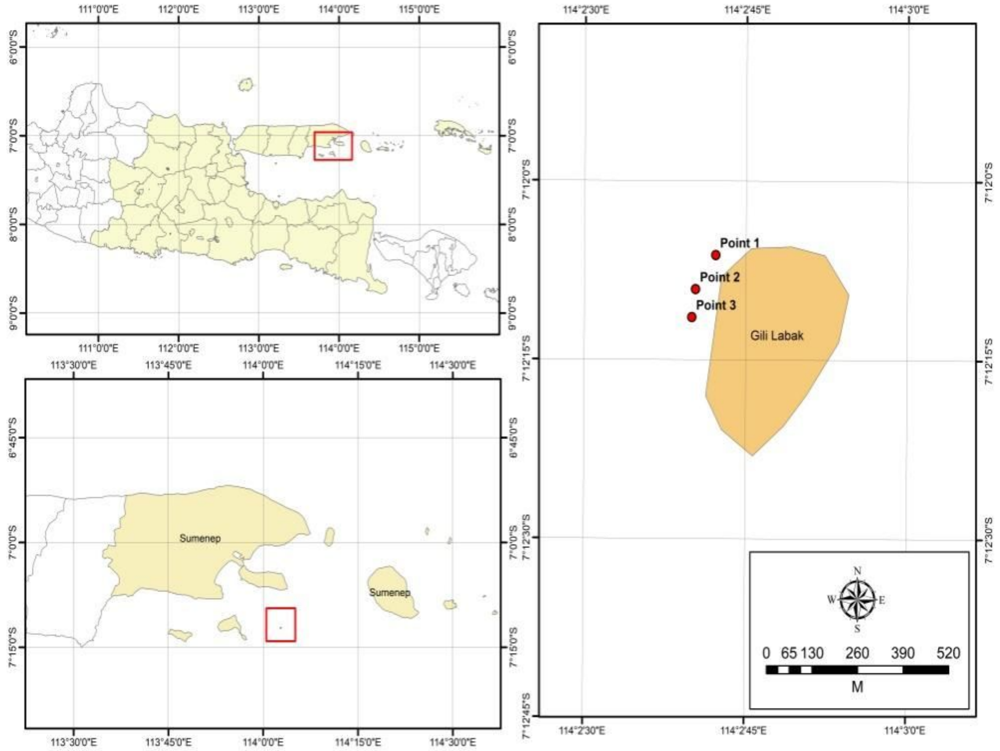

Figure 1. Map of study location at Gili Labak Island, Talango Sub-District, Sumenep Regency, Madura, East Java, Indonesia.

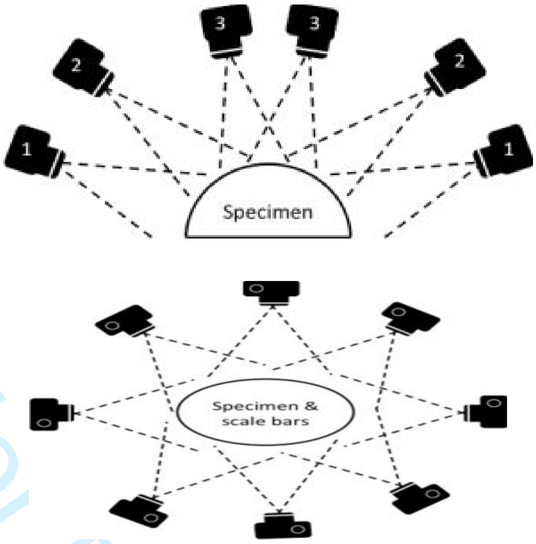

Figure 2. A schematic of the camera position used to produce 3D images (Ahmad et al. 2020).

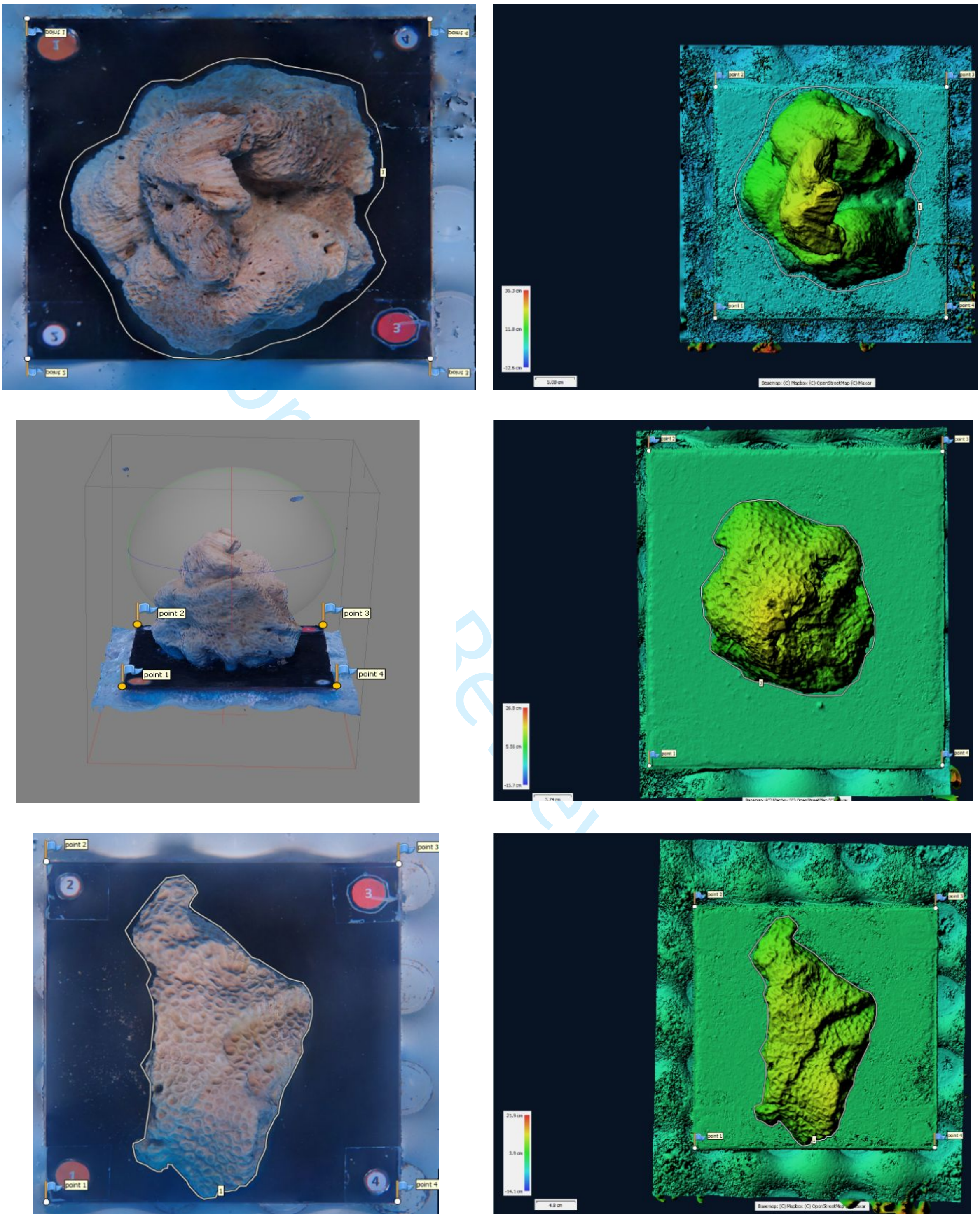

Figure 3. Results of DEM analysis and 3D photos of (dead) coral reefs with AMP software.

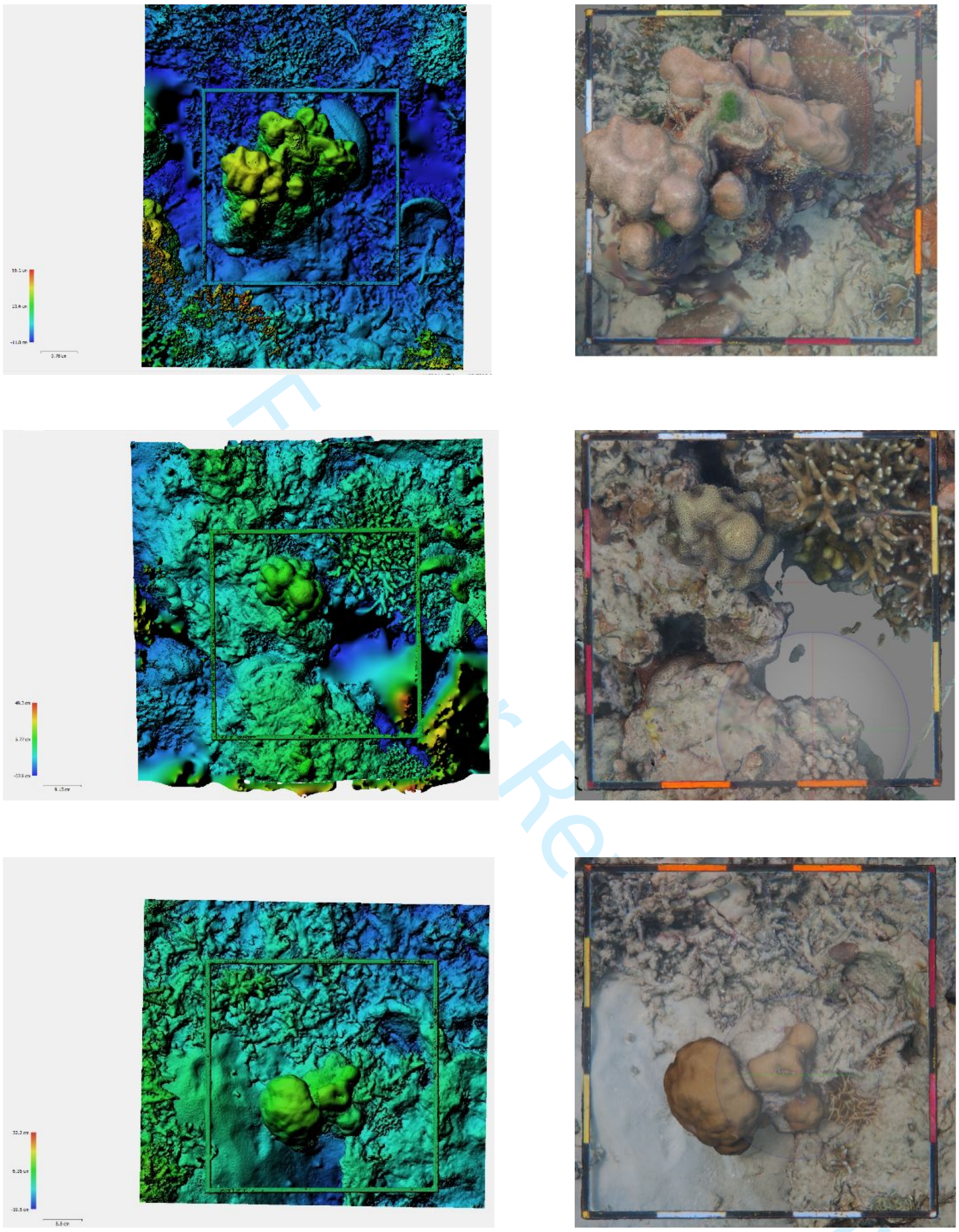

Figure 4. Results of DEM analysis and 3D photos of coral reefs in Gili Labak Island, Sumenep, Madura.

akhmad taufiq mukti <akhmad-t-m@fpk.unair.ac.id>

Biodiversity - Decision on Manuscript ID TBID-2023-0005

Biodiversity <onbehalfof@manuscriptcentral.com> Tue, Feb 7, 2023 at 10:36 PM
Reply-To: aitkense@biodiversityconservancy.org
To: akhmad-t-m@fpk.unair.ac.id, atm.mlg@gmail.com

07-Feb-2023

Dear Dr Mukti,

Thank you for resubmitting your paper to Biodiversity.

I am delighted to inform you that your paper has now been accepted by the Biodiversity, subject to revision along the lines suggested below, and the reviewer comments at the end of this letter.

I would be grateful if you could now provide a final paper following (Journal) guidelines, with a Title page containing authors affiliation and e-mail address (page 1), followed by Abstract and Key Words (page 2), and full text, all in the same document. Only tables and figures are to be included as a separate document.

To provide your final version, please click on the link below:
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This will direct you to the first page of your revised manuscript.
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IMPORTANT: Your original files are available to you when you upload your revised manuscript. Please delete any redundant files before completing the submission.

Because we aim for the timely publication of manuscripts submitted to Biodiversity, please upload your revised manuscript as soon as possible and before 21-Feb-2023.

Once again, thank you for submitting your manuscript to Biodiversity and I look forward to receiving your revision.

Sincerely,
Stephen Aitken
Managing Editor, Biodiversity Journal
aitkense@biodiversityconservancy.org, aitkense@gmail.com

Reviewer(s)' Comments to Author:

Reviewer: 1

Comments to the Author
Please check the comments provided

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akhmad taufiq mukti <akhmad-t-m@fpk.unair.ac.id>

Reminder: Your Revision for Biodiversity is due on in two weeks on 21-Feb-2023

1 message

Biodiversity <onbehalfof@manuscriptcentral.com> Wed, Feb 8, 2023 at 1:08 PM
Reply-To: rtrueman@biodiversityconservancy.org
To: akhmad-t-m@fpk.unair.ac.id, atm.mlg@gmail.com
Cc: rtrueman@biodiversityconservancy.org

08-Feb-2023

Dear Dr Akhmad Taufiq Mukti:

Recently, you received a decision on Manuscript ID TBID-2023-0005, entitled "Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia." This email is simply a reminder that your revision is due in two weeks on 21-Feb-2023.

To start the revision, please click on the link below:

*** PLEASE NOTE: This is a two-step process. After clicking on the link, you will be directed to a webpage to confirm. ***

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This will direct you to the first page of your revised manuscript in your Author Centre. The manuscript and decision letter are located here also.

This link will remain active until you have submitted your revised manuscript. If you have already begun a revision, you can click on the link to continue your revision. Please note that your draft will appear in the “Revised Manuscripts in Draft” queue in your Author Centre.

If it is not possible for you to submit your revision by 21-Feb-2023, we will consider your paper as a new submission.

Please contact the Editorial Office if you are unable to submit within this time.

Sincerely,
Rebecca Trueman
Biodiversity Journal Editorial Office
rtrueman@biodiversityconservancy.org

akhmad taufiq mukti <akhmad-t-m@fpk.unair.ac.id>

Biodiversity - Manuscript ID TBID-2023-0005.R1 has been submitted online

1 message

Biodiversity <onbehalfof@manuscriptcentral.com> Mon, Feb 20, 2023 at 11:27 AM
Reply-To: rtrueman@biodiversityconservancy.org
To: akhmad-t-m@fpk.unair.ac.id, atm.mlg@gmail.com

19-Feb-2023

Dear Dr Mukti:

Your manuscript entitled "Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia" has been successfully submitted online and is presently being given full consideration for publication in Biodiversity.

Your manuscript ID is TBID-2023-0005.R1.

Please mention the above manuscript ID in all future correspondence or when calling the office for questions. If there are any changes in your street address or e-mail address, please log in to ScholarOne Manuscripts at https://mc.manuscriptcentral.com/tbid and edit your user information as appropriate.

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Thank you for submitting your manuscript to Biodiversity.

Sincerely,
Biodiversity Journal Editorial Office

LETTER OF RESPONSE TO REVIEWER

Manuscript title : **Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia**
Manuscript ID : TBID-2023-0005

Dear
Editor-in-Chief of Biodiversity

Thanks for the corrections and suggestions that have been given to our manuscripts. The author's responses to corrections and suggestions of reviewer have been mentioned in the article with blue-coloured words or sentences.

Introduction

1. What does that imply? (QT) in page 2, line 40
   Authors response: We have revised the word in manuscript (page 2, paragraph 3, line 2): "quadratic transect (QT)"

Results

1. I think the authors mismatched the table...we could not find the weight of corals, in page 7, lines 29-30.
   Authors response: We have revised the word in manuscript (page 8, lines 1-2): "Table 3"

Discussion

1. Your research is about determining the volume of dead corals as a tiny part of coral reefs...so i does not make any sense you claimed coral reefs, in page 8 line 54.
   Authors response: We have revised and deleted word "reefs" in manuscript (page 8, paragraph 1, line 3)

2. Coral or coral reefs?...two different things, in page 8 line 54
   Authors response: We have revised and deleted word "reefs" in manuscript (page 8, paragraph 1, line 3).

3. You sure?.....check this 3D scanning as a highly precise, reproducible, and minimally invasive method for surface area and volume measurements of scleractinian corals, in page 9 line 3
   Authors response: We have revised and mentioned sentences in manuscript (page 9, paragraph 1): "As the study results of Reichert et al. (2016) on scleractinian corals show that 3D method has highly precision and easy to reproduce for invasive measurement of corals surface area and volume with a fast process." and page 10, paragraph 1: "Reichert et al. (2016) also stated that 3D method has highly precision and reproducible for measuring the surface area and volume of corals."

4. Did the authors compare any significant different between the weight of dead corals with the estimated one?, in page 9 line 40
   Authors response: We have mentioned sentences in the Materials and methods of manuscript (page 4, paragraph 1, lines 4-6): "The 32 massive coral colonies were weighed to obtain the modeling test data. Furthermore, the data were used to estimate the weight of massive live corals on Gili Labak Island."

5. Precision means if you repeat the same object for many times randomly, the result will be the same....did you do that on any corals many times?, in page 9 line 40
   Authors response: We have mentioned sentences in the Materials and methods of manuscript (page 4, paragraph 1, line 6): "Data processing through 3D was carried out repeatedly."

6. So why yours was higher than Hatcher?, in page 10 line 10
   Authors response: We have revised and mentioned sentences in manuscript (page 10, paragraph 2): "The number of cameras used also determines the results. In this study, only 1 camera was used, while the previous studies by Hatcher et al. (2020) and Figueira et al. (2015) used 5 cameras with high technology to capture underwater objects. Therefore, the RMSE value in this study had higher compared to previous studies."

7. of what?...RMSE or MAPE?, in page 10 line 13
   Authors response: We have added words "of RMSE" in manuscript (page 10).

8. Please give indication why yours was higher than Hatcher and Figueria...the smaller RMSE, the better fit between the predicted and actual values., in page 10 line 16
   Authors response: We have revised and mentioned sentences in manuscript (page 10, paragraph 2): "The number of cameras used also determines the results. In this study, only 1 camera was used, while the previous studies by Hatcher et al. (2020) and Figueira et al. (2015) used 5 cameras with high technology to capture underwater objects. Therefore, the RMSE value in this study had higher compared to previous studies."

9. Authors shall explain the weakness the method used so that readers can have their own opinions and it is also important for potential development in the future, in page 10 line 30
   Authors response: We have revised and mentioned sentences in manuscript (page 10, paragraph 3):"The 3D method has many advantages, but this method also has several weaknesses, including longer analysis and requires more software that is sophisticated, high-spec computer devices, and special skills in underwater data collection through diving."

Table 3

1. It is better to provide the bar chart comparing both volumes, are they significant?, in page 19 line 3.
   Authors response: We have revised word in the Table 3 of manuscript (page 19): "weight", so no both volume to compared.

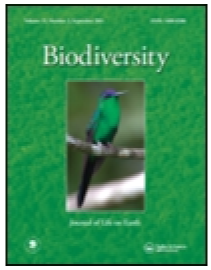
We have added and mentioned sentences in the Materials and methods of manuscript to explain (page 5, paragraph 2) “This analysis was used to determine the conversion from volume to weight of corals in the field. Conversion from volume to weight of corals was obtained to the best value of non-linear regression.”

2. If it is volume, why is the unit in g? in page 19 line 3.
   Authors response: We have revised word in the Table 3 of manuscript (page 19): “weight”.

Thus authors responses on comments, corrections, and suggestions of reviewers, we expect the reviewers were pleased and understand it and we hope that this article will be corrected further. Thank you very much.

Best regards,

Akhmad Taufiq Mukti



Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

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ABSTRACT

This study aimed to non-destructively measure the weight of massive (live) corals through three-dimensional (3D) modeling. The 3D models were constructed using the volumes and weight of massive (dead) corals. The study was conducted through photographs, 3D analysis, and weighing 32 massive (dead) coral samples. Volume and weight were modeled using linear and non-linear regressions, and their accuracy was tested using root mean square error (RMSE) and mean absolute percentage error (MAPE). This study showed that the weight of massive (live) corals could be measured using a 3D model of the massive (dead) coral's volume and the weight mainly through regression, polynomial, and geometric equations. The power/geometric equation is a more suitable approach to the actual value of coral weight. Linear regression obtained an average weight of 6.13 kg per plot. 3D modeling can be widely applied to measure the massive corals in the deep sea.

Keywords: Corals; Gili Labak Island; three-dimensional modeling; volume; weight

Introduction

The preservation of coral reef ecosystems is critical because many people in the twenty-first century will rely on these resources for food production, coastal protection, and the survival of their ecosystems (Kleypas et al. 2021). Coral reefs are among the most diverse and threatened ecosystems (Hoegh-Guldberg et al. 2019). Therefore, monitoring its responses to various threats and disturbances is critical for management and conservation. Understanding the best methods for measuring changes in corals, ecosystems, and their functions is a challenge. An emerging method for exploring colony-scale growth patterns employs underwater photogrammetry to create digital models of coral colonies (Lange and Perry 2020). Acoustic methods are currently widely used to detect the presence of underwater objects. Their systems work exceptionally well.

Developing methodologies that allow the incorporation of three-dimensional (3D) metrics into coral reef monitoring is critical. One of the most commonly used metrics for assessing reef health is the proportion of live coral cover on reefs (Leujak and Ormond 2007). It is used as a proxy for calculating coral reef biomass and grows on the capabilities of most techniques used to evaluate linear or horizontal planar estimates. However, 2D alone is insufficient to estimate coral reef cover (Bamford and Forrester 2003), whereas 3D coral reefs provide valuable information on health (Dickens et al. 2011). The 3D surface and volume provide more accurate coral abundance statistics and allow for more accurate mapping of coral reef changes.

Manta tow, line intercept transect (LIT), point intercept transect (PIT), belt transect (BT), and quadratic transect (QT) are standard research methods in coral reefs, depending on the purpose. The 3D modeling method is an advancement and modification of the underwater photo transect (UPT) method, which uses 3D photographs to identify coral species. As a result, 3D surface area and volume can provide more accurate metrics of coral abundance information and allow for more accurate capture of changes in coral reefs. This modeling is the most effective method for assessing coral reef damage and estimating carbon stocks. Comparison, photogrammetry, and 3D models offer a quick, simple, low-cost, and non-invasive method (Lange and Perry 2020). This study is a cost-effective and non-invasive method for accurate geometrical measurements of corals. Because it is impossible to obtain photos of all coral surfaces and know the estimated weight of corals using a 3D approach, accuracy is highly dependent on the complexity of the coral reef. This study aimed to non-destructively measure the weight of massive (live) corals through 3D modeling.

Materials and methods

Research location

This study was conducted at 8 to 12 m on Gili Labak Island, Talango Sub-District, Sumenep Regency, Madura, East Java, Indonesia. The map of the study location is shown in Figure 1.

Sampling

A 3D model was created using 30 colonies of massive dead corals that were weighed to determine their weight and photographed for analysis in the Agisoft Methasape Professional (AMP) software. The volume and weight results were used to find the linear and regression non-linear equations. Second, 30 coral samples were used for the accuracy test, and volume was measured in the pond using an Olympus TG-6 camera on a transect of 30 cm × 30 cm and in the field using the frame 50 cm × 50 cm for live coral. (Figueira et al. 2015).

3D measurement of massive corals

AMP software was also used to analyze the results of coral photos. First, the image quality of underwater photos was estimated using the image's sharpness, exposure, focus, resolution, and depth of field. The camera and build dense cloud (BDC) were then synced with the software and scaled with a scale. Third, a dense point cloud was created using depth information from each camera and a densification algorithm. Fourth, 3D nets were built. Create texture (optional), but performing 3D measurement and analysis is not required. Planar projections by orthographic views were used to isolate a "cleaning" coral colony model from other reconstructed elements such as reef foundations, and AMP editing oriented all models. Exported models were used for quantitative analysis and volume calculations (Kabiri et al. 2020; de Oliveira et al. 2021).

Before taking the 3D photo in the pond, the coral was weighed. The data was collected to create a model using linear and non-linear regression. Following that, 32 massive corals from the second sample were weighed for root mean square error (RMSE) and mean absolute percentage error (MAPE) tests. The 32 massive coral colonies were weighed to obtain the modeling test data. Furthermore, the data were used to estimate the weight of massive live corals on Gili Labak Island. Data processing through 3D was carried out repeatedly.

Underwater camera photo

Coral colonies were photographed from every angle possible, including above and below. As shown in Figure 2, the camera was positioned at each object's angle (Burns et al. 2015). The 3D volume was measured by diving to a depth of 8 m and collecting 32 coral colonies. A schematic of the camera position is used to generate 3D images, as shown in Figure 2 (Ahmad et al. 2020).

Massive corals were photographed in the pond using a 30 cm × 30 cm transect, while coral were photographed in the field using a 50 cm × 50 cm transect (Ahmad et al. 2020). Continuous underwater photography from oblique planes and angles captured the entire colony surface (Figure 2), with 70 to 80% overlap (Bythell and Pan 2001; Burns et al., 2019). All photos were uploaded to the AMP software, and the camera was calibrated using metadata-derived focus information. Furthermore, the photos were aligned using an algorithm capable of detecting invariant features that overlap between consecutive photos. A geometric projection matrix was created using invariant features and the position, and the camera orientation for each photograph was determined according to Westoby et al. (2012). Extrinsic parameters calculated during the photo-alignment process were combined with intrinsic and focal parameters obtained from the metadata to create the 3D geometry from 2D images (Stal et al. 2012). Bookmarks were used as a manual for all ground control points (GCP), and the location of each marker in all photos containing the GCP was reviewed and corrected. Values of x, y, and z for each GCP were entered into the software to optimize alignment and ensure the resulting model's accurate interior and exterior orientation.

The pattern of relationships between independent and dependent variables on the 3D weight and volume of coral reefs was determined using regression analysis (Scott et al. 1991). This analysis was used to determine the conversion from volume to weight of corals in the field. Conversion from volume to weight of corals was obtained to the best value of non-linear regression. Regression analysis was divided into linear and non-linear regressions based on the relationship pattern. When the variables have power/geometric, the model is called a non-linear regression. When a non-linear regression model in parameters is differentiable, the result is always a function in parameters, as stated. The non-linear regression in parameters was calculated according to Scott et al. (1991)**.** Statistical analysis was performed on three regression and non-linear regression equation models, linear, polynomial, and power/geometric, based on 3D volume and weight photographs of massive (dead) corals.

Root mean square error (RMSE) test.

An accuracy test was carried out to determine the best equation for estimating the volume and weight of corals. Using the RMSE test, an accuracy test was used to determine the error value of the regression equation. Then, 3D volume photographs were compared to 3D weight photographs. The RMSE equation was used:

$$\text{MSE} = \sqrt{\frac{i}{n}\sum_{i=1}^{n}(x_1 - y_1)^2}$$

$$\text{RMSE}\ (\%) = \frac{RMSE}{\acute{Y}} \times 100$$

Note: MSE = mean square error, RMSE = root mean square error, x_1 = 3D measurement result value, y_1 = 3D value prediction, and Ý = average 3D measurement results (Suprayogi et al. 2014; Gurchiek et al. 2017).

Mean absolute percentage error (MAPE) test

MAPE was used to evaluate the estimation of the results and determine the accuracy of the estimated number and the realization rate. The following formula was used to calculate the value:

$$\text{MAPE}\ (\%) = \frac{\sum_{t=1}^{n} \frac{[A_t - F_t]}{At}}{n} \times 100$$

Note: MAPE = mean absolute percentage error, Ft = estimated value at time t, At = actual value at time t, and n = total data (t = 1, 2, .., n).

The MAPE test model's accuracy was measured using three criteria: very accurate (MAPE<5%), accurate (5%<MAPE<10%), and inaccurate (MAPE>10%) (Nabillah and Ranggadara 2020).

Data analysis

3D photos were taken in a small pond with 30 colonies to find linear and non-linear regression models, 30 colonies for accuracy tests, and 32 samples of massive coral colonies for comparison (Fukunaga and Burns 2020). The digital elevation model (DEM) is a raster grid that references the subject surface's starting point. This modeling allows for the removal of objects from the surface, resulting in a 3D model with a smooth surface. If the DEM image does not appear during analysis, the volume results will not be displayed, and the analysis cannot be continued in the AMP software. The average number of photos analyzed in 3D for each coral colony was 93 to 98. The photos were then analyzed in software (Lange and Perry 2020) using AMP software (Kabiri et al. 2020; de Oliveira et al., 2021).

Results

Develop a 3D volume model of dead coral samples collected in the field. The use of dead coral samples to avoid causing harm to the coral ecosystem at the study site. Experiments with a frame binding point of 30 cm × 30 cm yielded photographs of dead coral samples. The number was indicated as a binding point in the corner of the frame; the binding point's purpose is to serve as a GCP for 3D photo analysis. The results of the dead coral colonies analysis are presented in Figure 3.

The results of underwater analysis of 3-dimensional images captured with AMP software on 30 massive (dead) coral colonies in a pond yield 3D modeling volumes on coral samples, with images captured of the entire coral surface. Each coral sample contains an average of 102 photographs. Table 1 shows the results of the RMSE control point analysis on the 3D photo analysis of corals in the pond.

The photos were analyzed in 3D using the AMP 1.7.4 software, and the RMSE control point value was calculated. Based on analysis, the 3D photo error in the water (small pond) is less than 1 mm. The 3D photo analysis yielded an average RMSE of corals for photos in small ponds with an average of 102 photos, an average X error of 0.29206 mm, Y error of 0.50167 mm, Z error of 0.34566 mm, XY error of 0.59070, and a total error of 0.72119 mm. The water's influence can affect the camera to distort. Table 2 displays the results of linear and non-linear regression analysis of weight and volume using AMP software.

Table 2 showed that the model with the best accuracy of power/geometric resulted in $y = 2.451x^{0.898}$, $R^2 = 0.916$ with RMSE test of 251.20 g, %RMSE of 18.10%, and MAPE of 19.17%, while linear regression resulted in $y = 0.964x + 314.470$, $R^2 = 0.912$, RMSE of 284.50 g, %RMSE of 20.50%, and MAPE of 27.43%. Meanwhile, the polynomial resulted in $y = 0.001x^2 + 1.235x + 49.448$ $R^2 = 0.915$ with RMSE test of 354.30 g, %RMSE of 25.5%, and MAPE of 20.0%. Based on its orthographic projections, the coral colony orientation is utilized to calculate volume. On the other hand, growth orientation is influenced by environmental factors such as habitat complexity, slope, and light plane, potentially leading to estimation bias.

Coral samples were also weighed to calculate the mass of massive corals. All coral samples from the 3D photo volume and the weight of dead corals were used to obtain a model for the estimated live coral weight. The volume of 3D photos and the weight of corals in (Table 3) are used to construct a model using linear and non-linear regression equation approaches.

The volume of the coral could not be directly considered in the 3D photo analysis using AMP software due to the coral has a complex shape and concave bottom with small cavities. Calculating the volume of a 3D photo model is usually invisible and legible. As a result, a conversion is required to minimize errors when using a regression approach. The power/geometric conversion of the model from the initial data to the linear regression equation model is y = 2.451x0.898, R2= 0.916 with RMSE test of 251.20 g, %RMSE of 18.10%, and MAPE of 19.17%.

Data on corals

The results of the analysis of live coral colonies on Gili Labak Island can be seen in Figure 4. The modeling application and field data collection were tested on Gili Labak Island. Photos were taken by diving at depths ranging from 8 to 12 m with a sample of 32 coral colonies. The iron frame used is 50 cm × 50 cm or 2500 cm^2, with a mark on each corner of the frame serving as a binding point for the photo and making analysis more accessible in the AMP software. The results of the 3D analysis are seen in Table 3.

The model conversion from the initial data using the power/geometric equation model was $y = 2.451x^{0.898}$ with $R^2 = 0.916$. In Gili Labak Island, the average weight of coral volume produced is 6.13 kg per plot, and the total coral volume for the 32 plots is 169.92 kg, with a maximum value of 32.92 kg per plot and a minimum value of 0.04 kg per plot.

Discussion

The diversification of new methods in coral reef research is increasing. In this study, a new method was used to assist other examiners who do not have direct experience in identifying coral in the sea, allowing novices to process the data and identify coral on land without direct identification in the field. One advantage of the 3D method used in this study is the ability to obtain more controlled and verifiable data and data on the volume of coral reefs that were never obtained using previous methods. As the study results of Reichert et al. (2016) on scleractinian corals show that 3D method has highly precision and easy to reproduce for invasive measurement of corals surface area and volume with a fast process.

This study uses DEM results from AMP software to determine the volume of massive coral colonies and then models massive coral weight in Gili Labak Island, Sumenep, Madura. 3D modeling is the most effective data presentation method for describing coral reef damage. Acoustic methods are now commonly used to detect the presence of underwater objects. This system is beneficial for exploring the underwater environment (Kornder et al. 2021).

The emerging method of developing digital models of coral colonies using underwater photogrammetry provides a new and non-invasive way to examine colony-scale growth patterns and fill existing knowledge gaps (Lange and Perry 2020). The main difficulty in coral reef ecology is estimating the abundance and composition of communities living in such complex ecosystems (Kornder et al. 2021). This study used technological advances to identify volumes in massive coral colonies using a 3D model. The advancement of photogrammetric technology has created a viable and practical method for exploring coral reefs (House et al. 2018). The structural parameters of reef surfaces and organisms have been shown to have relatively high accuracy when using photogrammetry in combination with underwater photogrammetry (Veal et al. 2010; Bryson et al. 2017).

Testing accuracy and precision are critical in any research, including underwater photogrammetry of corals. The accuracy and precision of the geometry obtained from the massive coral's 3D model were tested in this study. As a result, 3D measurement is an accurate quantitative study of the physiology and various sizes of coral colonies, and it can be done in situ. This technique could also be used to measure morphometrics of branching species, such as branch spacing, density, branch length, and branch angle. The 3D method precisely measures architectural complexity, topography, rugosity, volume, and other critical structural properties in ecosystems (Burns et al. 2015). This method reconstructs the 3D structure of corals and habitat-forming organisms at high resolution and accuracy by using a series of overlapping images taken from multiple perspectives (Bryson et al. 2017). Reichert et al. (2016) also stated that 3D method has highly precision and reproducible for measuring the surface area and volume of corals.

This study also included the RMSE test results, which had a value of 18.10% and a MAPE of 19.17%, whereas Hatcher et al. (2020) produced a relative RMSE of 0.013%. This result produced a higher value of RMSE compared to Figueira et al. (2015), who obtained 10% results from bottle coral measurements. The number of cameras used also determines the results. In this study, only 1 camera was used, while the previous studies by Hatcher et al. (2020) and Figueira et al. (2015) used 5 cameras with high technology to capture underwater objects. Therefore, the RMSE value in this study had higher compared to previous studies.

Photogrammetry was initially developed and applied in terrestrial settings, but it has since become a valuable tool for creating 3D models of bathymetry and underwater habitats. Because complete recordings of all surfaces are not possible, complex corals could not be observed adequately with this model. This is a non-invasive method for obtaining precise geometric measurements of corals and other irregular underwater objects (Bythell and Pan 2001). The 3D method has many advantages, but this method also has several weaknesses, including longer analysis and requires more software that is sophisticated, high-spec computer devices, and special skills in underwater data collection through diving.

Conclusions

The massive corals in the deep sea can be identified and measured using 3D modeling. This study will continue to calculate the carbon stock of coral reefs in the future. This method is a non-invasive, cost-effective, and timesaving approach to obtaining accurate coral geometric measurements. Due to the difficulty in obtaining complete photos of all surfaces, accuracy is highly dependent on the complexity of the coral reef.

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Author contributions

DI conceptualized, collected the materials, performed the experiment, measured parameters, analyzed the data, and prepared the manuscript draft; ATM conceptualized, designed, and analyzed the data, edited and corrected the final manuscript; SA corrected English Grammarly and proofread the manuscript draft; FFM designed and corrected the manuscript draft. All authors read and approved the final manuscript.

Disclosure statement

The authors declare that they have no conflict of interest.

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Table 1. RMSE control points on the results of 3D photo analysis in a small pond.

No coral	Number of photo	RMSE				
		X error (mm)	Y error (mm)	Z error (mm)	XY error (mm)	Total (mm)
1	97	0.55387	1.13955	0.77888	1.26703	1.48728
2	100	0.27418	0.18195	0.04357	0.32906	0.33193
3	96	0.86821	0.86821	2.64072	1.18693	2.89520
4	94	0.44546	0.40574	0.48895	0.60255	0.77597
5	102	0.16377	0.31121	0.01835	0.35167	0.35215
6	95	0.23989	0.26469	0.32463	0.35722	0.48270
7	89	0.01553	0.23047	0.15672	0.23099	0.27913
8	96	0.31492	0.28618	0.41279	0.42553	0.59285
9	110	0.26506	0.24065	0.15519	0.35801	0.39020
10	82	0.19772	0.57799	0.20527	0.60183	0.63587
11	89	0.06381	0.21831	0.12998	0.22744	0.26196
12	115	0.26025	0.42471	0.20647	0.49811	0.53921
13	114	0.26427	0.30750	0.20589	0.40546	0.45474
14	114	0.10470	0.33880	0.18488	0.35461	0.39992
15	95	0.15410	0.33145	0.23749	0.36552	0.43590
16	100	0.10025	0.36274	0.18387	0.37634	0.41886
17	102	0.05425	0.34436	0.16343	0.34861	0.38502
18	104	0.11650	0.13726	0.14757	0.18004	0.23279
19	93	0.30765	0.43068	0.06607	0.52928	0.53339
20	100	0.26892	0.42773	0.26986	0.50525	0.57280
21	110	0.08382	0.15316	0.26245	0.17459	0.31522

22	113	0.08055	0.18929	0.28779	0.20571	0.35375
23	114	0.16094	0.20679	0.04977	0.26204	0.26673
24	111	2.18783	5.24739	0.98116	5.68522	5.76926
25	110	0.14644	0.34430	0.68882	0.37415	0.52542
26	119	0.51075	0.23892	0.66404	0.56387	0.87115
27	94	0.10643	0.17073	0.18373	0.20119	0.27246
28	108	0.08465	0.21065	0.01163	0.22703	0.22733
29	101	0.07523	0.20130	0.13604	0.21490	0.25434
30	103	0.17461	0.25764	0.08381	0.31109	0.32218
Average	102	0.29206	0.50167	0.34566	0.59070	0.72119

Table 2. The volume of coral reefs from 3D photo analysis by weight.

Analysis	Massive coral reefs	Test data
Linear	$y = 0.964x + 314.470$	RMSE = 284.50 g
	$R^2 = 0.912$	%RMSE = 20.50%
		MAPE = 27.43%
Polynomial	$y = 0.001x^2 + 1.235x + 49.448$	RMSE = 354.30 g
	$R^2 = 0.915$	%RMSE = 25.50%
		MAPE = 20.00%
Power/geometric	$y = 2.451x^{0.898}$	RMSE = 251.20 g
	$R^2 = 0.916$	%RMSE = 18.10%
		MAPE = 19.17%

Table 3. The volume of 3D photos produced by AMP software and **weight** of coral conversion using a power/geometric model.

No.	The volume of 3D photo analysis (cm^3)	Coral weight estimation using power/geometric model (g)	Genus of coral
1	2951	3191.71	*Favia*
2	3173	3406.42	*Favites*
3	6045	6075.19	*Pavona*
4	39727	32924.42	*Favia*
5	26236	22687.22	*Leptoseris*
6	5402	5491.86	*Favia*
7	5125	5238.42	*Coscinaraea*
8	8601	8337.39	*Leptoria*
9	1825	2073.42	*Favia*
10	2564	2813.35	*Caulastrea*
11	2093	2344.78	*Caulastrea*
12	3937	4134.27	*Pavona*
13	13706	12666.88	*Montastrea*
14	1703	1948.57	*Montastrea*
15	23181	20301.18	*Favites*
16	4388	4556.98	*Favia*
17	2223	2475.09	*Psammocora*
18	2983	3222.76	*Goniastrea*
19	4112	4298.86	*Favia*
20	384	511.77	*Montastrea*
21	10421	9904.99	*Psammocora*

22	4016	4208.66	*Psammocora*
23	7715	7562.26	*Coscinaraea*
24	21	37.69	*Leptoseris*
25	7036	6962.07	*Psammocora*
26	14529	13347.55	*Psammocora*
27	226	318.00	*Euphyllia*
28	969	1174.64	*Psammocora*
29	471	614.73	*Montastrea*
30	255	354.40	*Porites*
31	253	351.90	*Porites*
32	2509	2759.12	*Favia*

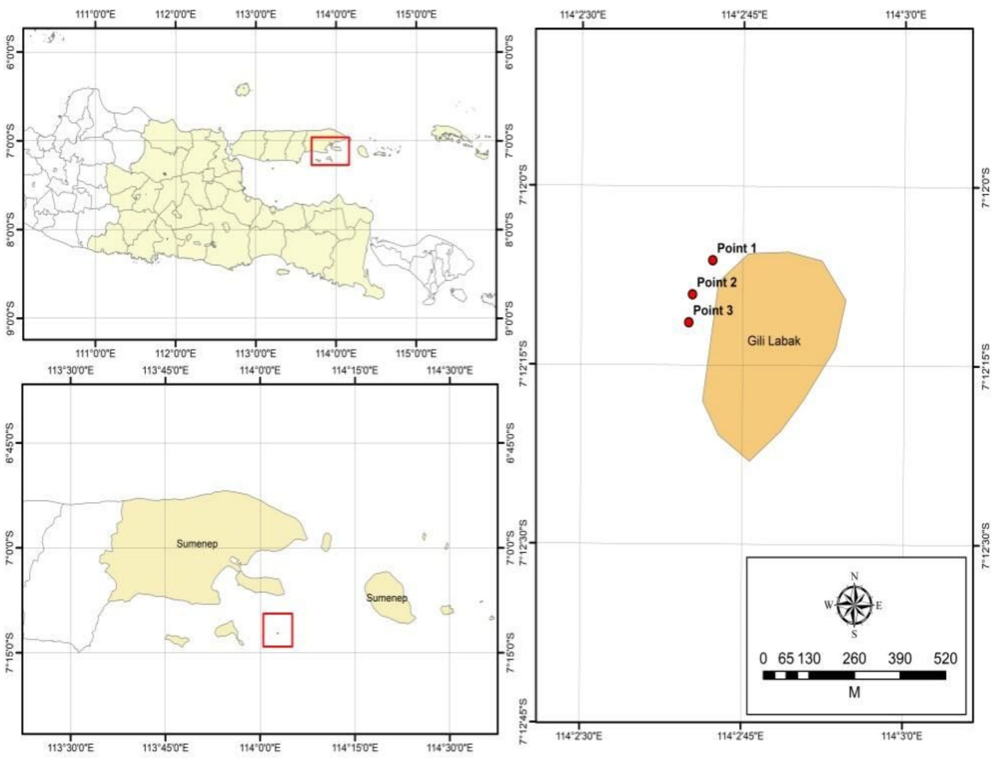

Figure 1. Map of study location at Gili Labak Island, Talango Sub-District, Sumenep Regency, Madura, East Java, Indonesia.

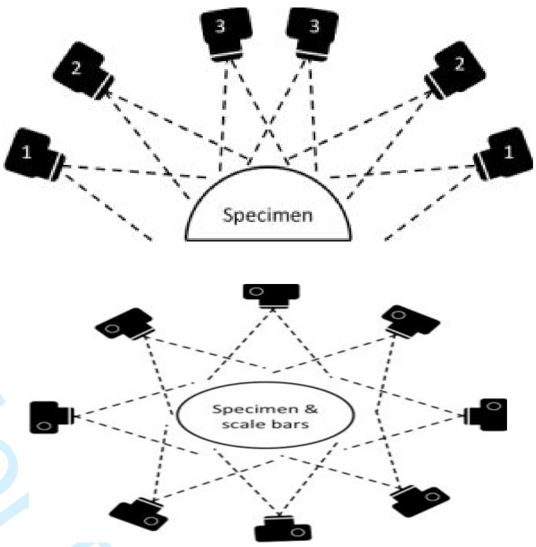

Figure 2. A schematic of the camera position used to produce 3D images (Ahmad et al. 2020).

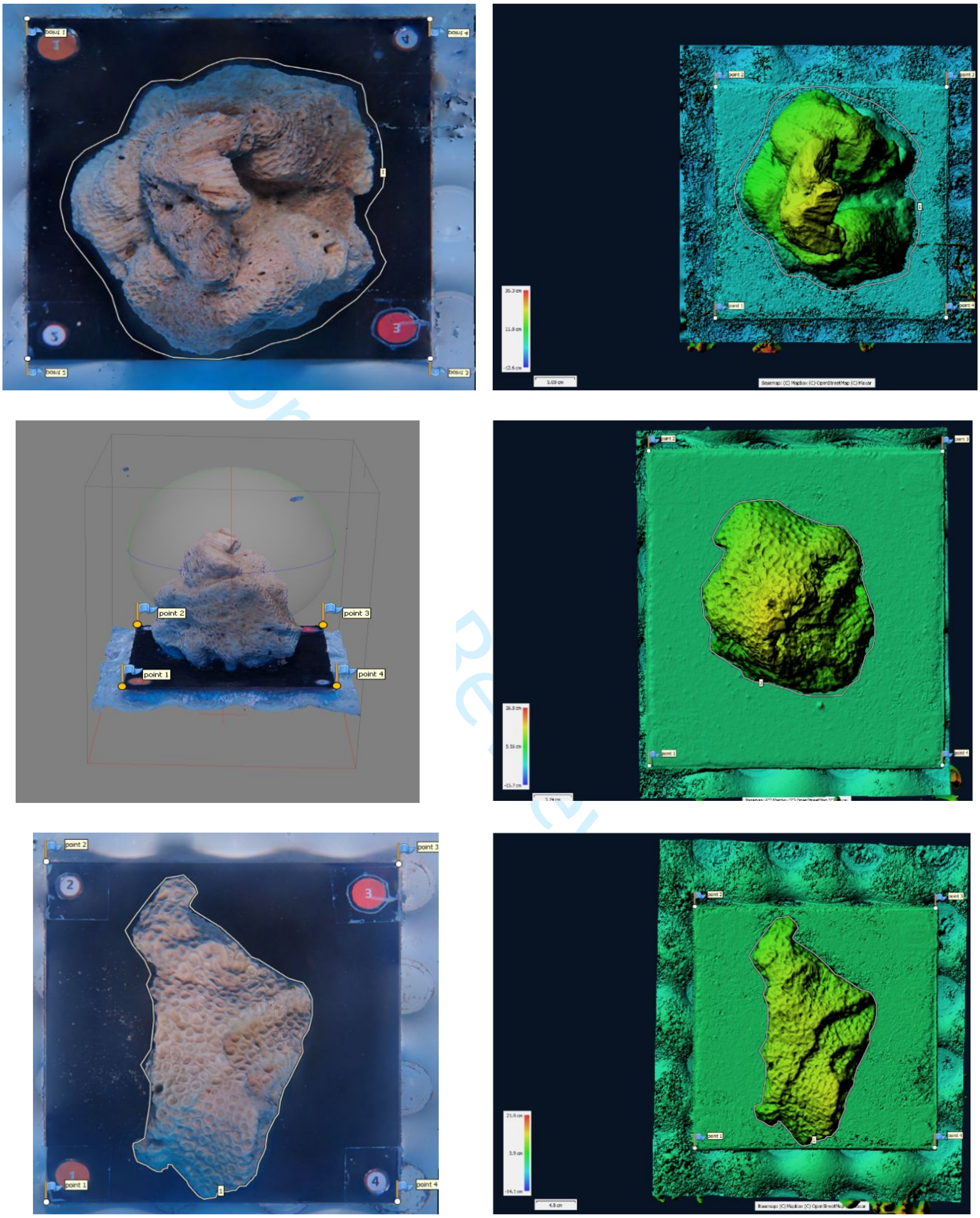

Figure 3. Results of DEM analysis and 3D photos of (dead) coral reefs with AMP software.

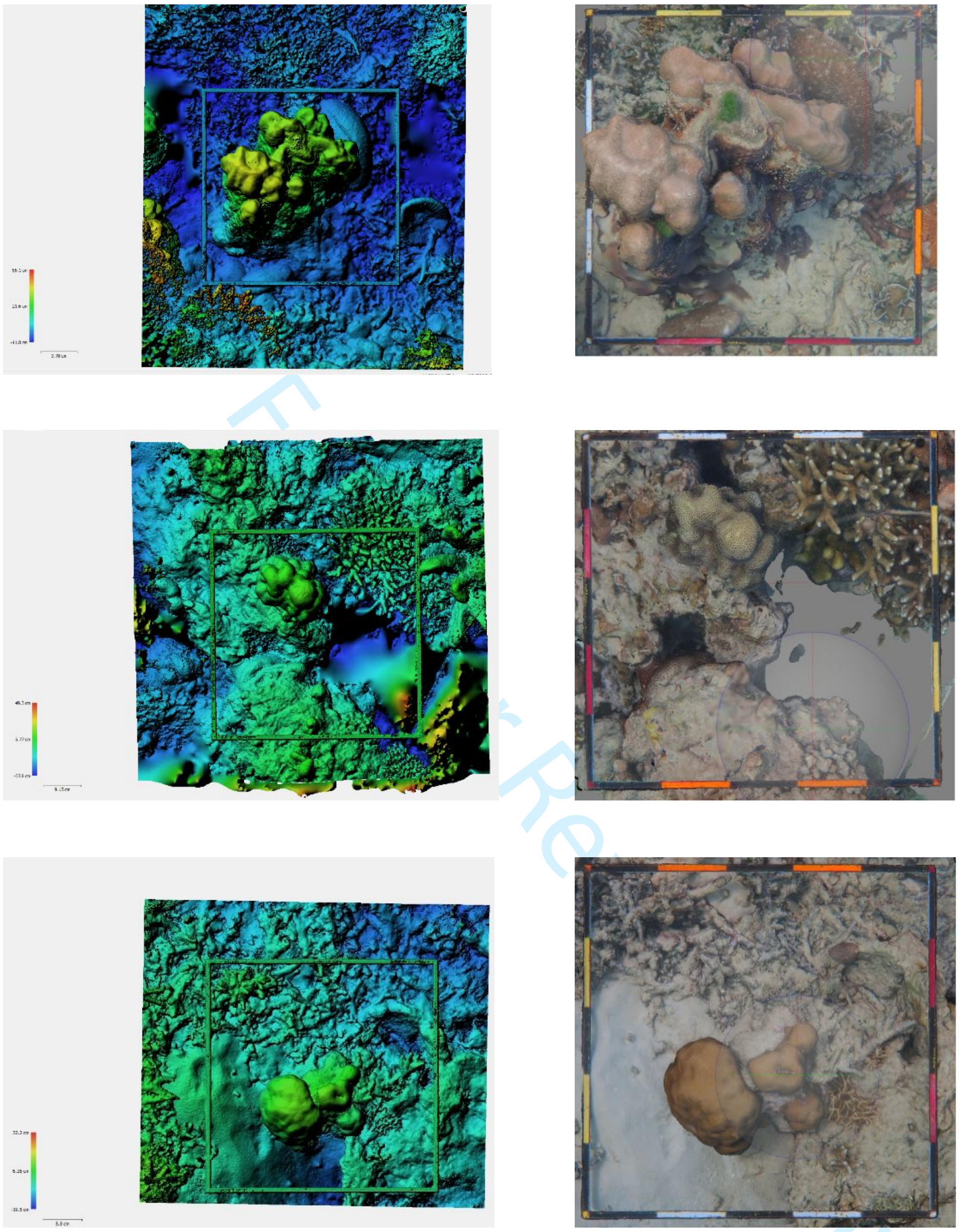

Figure 4. Results of DEM analysis and 3D photos of coral reefs in Gili Labak Island, Sumenep, Madura.

Table 1. RMSE control points on the results of 3D photo analysis in a small pond.

No coral	Number of photo	RMSE X error (mm)	Y error (mm)	Z error (mm)	XY error (mm)	Total (mm)
1	97	0.55387	1.13955	0.77888	1.26703	1.48728
2	100	0.27418	0.18195	0.04357	0.32906	0.33193
3	96	0.86821	0.86821	2.64072	1.18693	2.89520
4	94	0.44546	0.40574	0.48895	0.60255	0.77597
5	102	0.16377	0.31121	0.01835	0.35167	0.35215
6	95	0.23989	0.26469	0.32463	0.35722	0.48270
7	89	0.01553	0.23047	0.15672	0.23099	0.27913
8	96	0.31492	0.28618	0.41279	0.42553	0.59285
9	110	0.26506	0.24065	0.15519	0.35801	0.39020
10	82	0.19772	0.57799	0.20527	0.60183	0.63587
11	89	0.06381	0.21831	0.12998	0.22744	0.26196
12	115	0.26025	0.42471	0.20647	0.49811	0.53921
13	114	0.26427	0.30750	0.20589	0.40546	0.45474
14	114	0.10470	0.33880	0.18488	0.35461	0.39992
15	95	0.15410	0.33145	0.23749	0.36552	0.43590
16	100	0.10025	0.36274	0.18387	0.37634	0.41886
17	102	0.05425	0.34436	0.16343	0.34861	0.38502
18	104	0.11650	0.13726	0.14757	0.18004	0.23279
19	93	0.30765	0.43068	0.06607	0.52928	0.53339
20	100	0.26892	0.42773	0.26986	0.50525	0.57280
21	110	0.08382	0.15316	0.26245	0.17459	0.31522

22	113	0.08055	0.18929	0.28779	0.20571	0.35375
23	114	0.16094	0.20679	0.04977	0.26204	0.26673
24	111	2.18783	5.24739	0.98116	5.68522	5.76926
25	110	0.14644	0.34430	0.68882	0.37415	0.52542
26	119	0.51075	0.23892	0.66404	0.56387	0.87115
27	94	0.10643	0.17073	0.18373	0.20119	0.27246
28	108	0.08465	0.21065	0.01163	0.22703	0.22733
29	101	0.07523	0.20130	0.13604	0.21490	0.25434
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25	7036	6962.07	*Psammocora*
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30	255	354.40	*Porites*
31	253	351.90	*Porites*
32	2509	2759.12	*Favia*

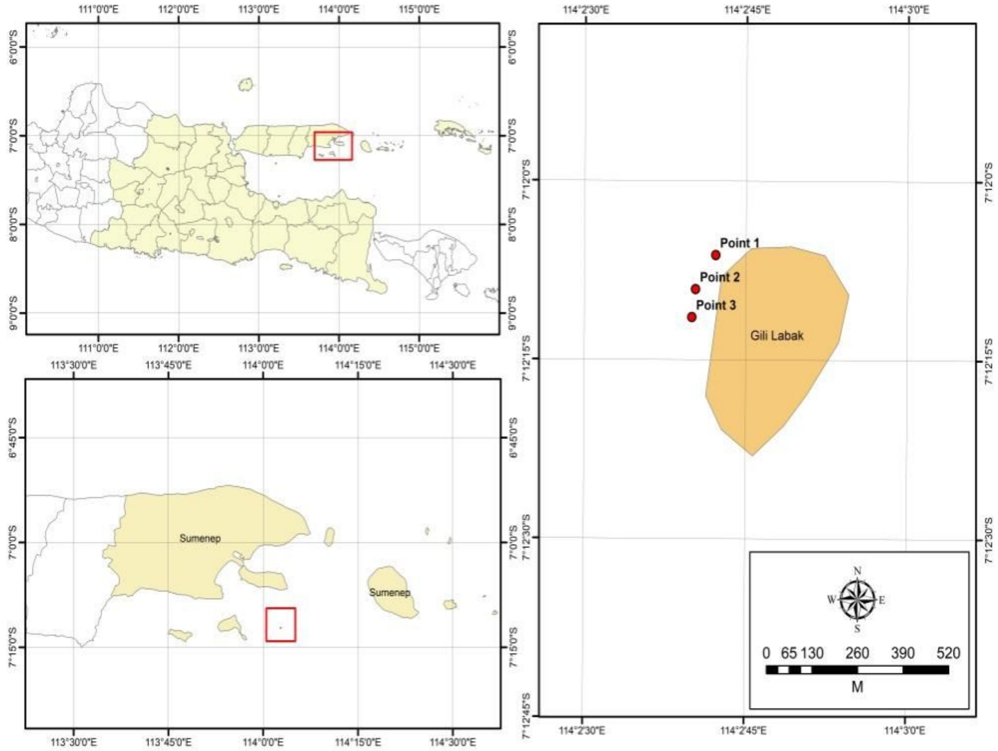

Figure 1. Map of study location at Gili Labak Island, Talango Sub-District, Sumenep Regency, Madura, East Java, Indonesia.

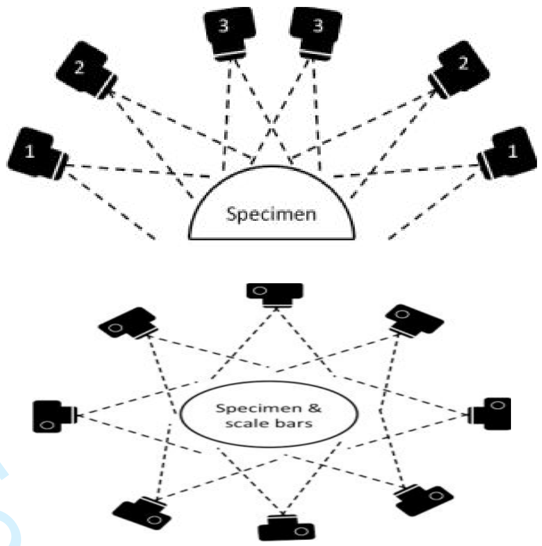

Figure 2. A schematic of the camera position used to produce 3D images (Ahmad et al. 2020).

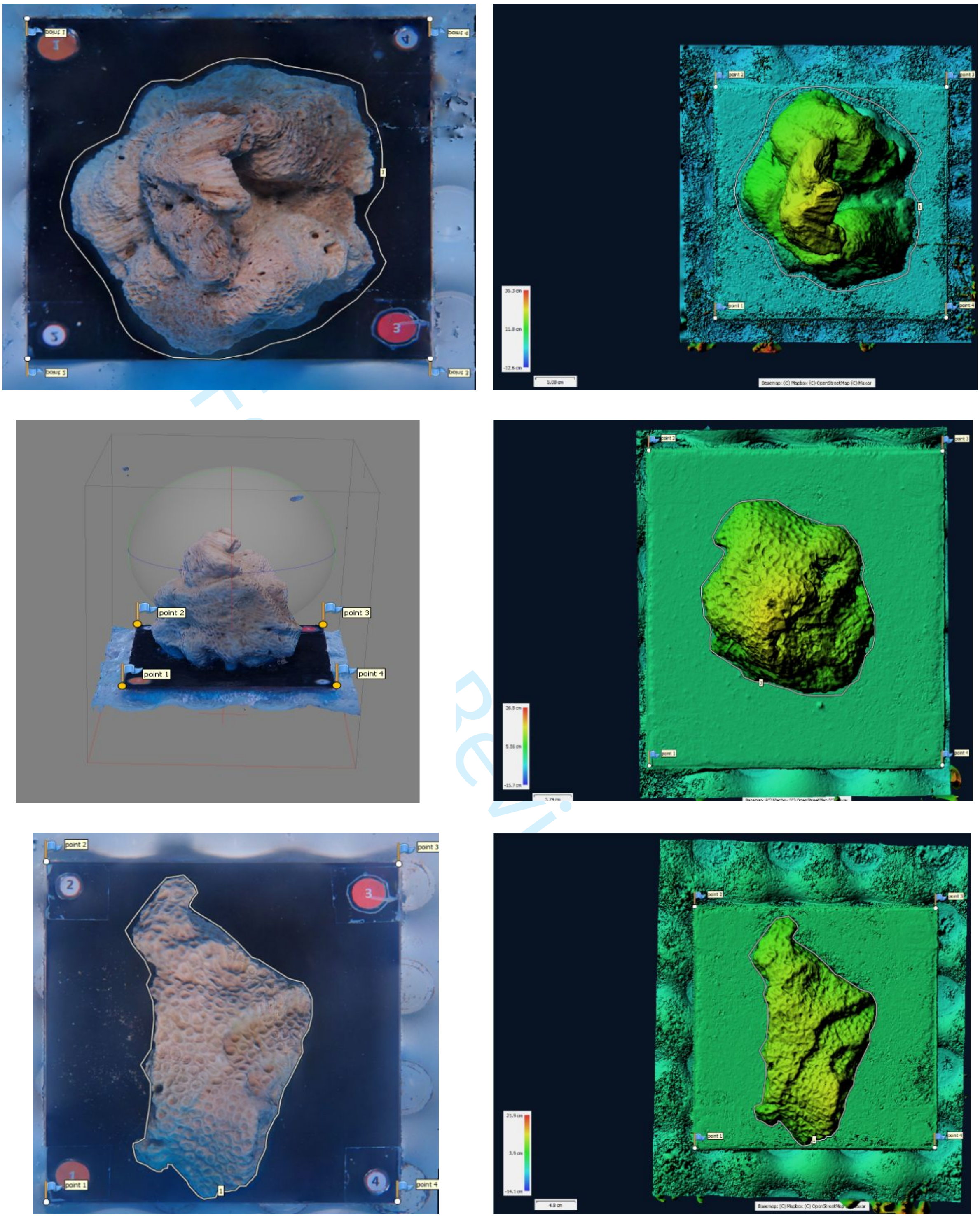

Figure 3. Results of DEM analysis and 3D photos of (dead) coral reefs with AMP software.

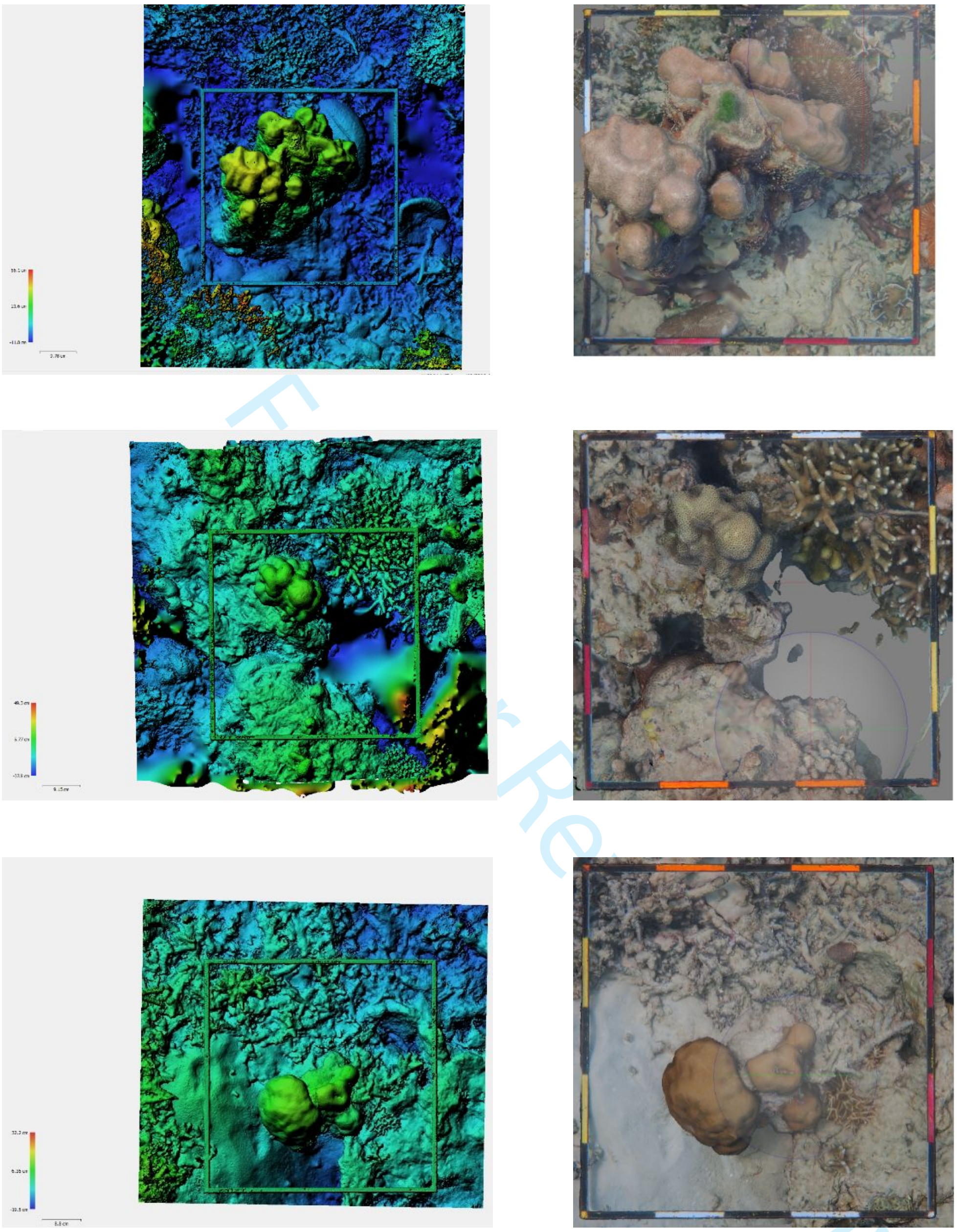

Figure 4. Results of DEM analysis and 3D photos of coral reefs in Gili Labak Island, Sumenep, Madura.

akhmad taufiq mukti <akhmad-t-m@fpk.unair.ac.id>

Biodiversity - Decision on Manuscript ID TBID-2023-0005.R1

1 message

Biodiversity <onbehalfof@manuscriptcentral.com> Tue, Feb 21, 2023 at 8:28 AM
Reply-To: rtrueman@biodiversityconservancy.org
To: akhmad-t-m@fpk.unair.ac.id, atm.mlg@gmail.com
Cc: rtrueman@biodiversityconservancy.org

20-Feb-2023

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Ref: Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

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Rebecca Trueman
Managing Editor, Biodiversity Journal

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To: akhmad-t-m@fpk.unair.ac.id

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Article: Three-dimensional (3D) modeling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

Journal: *Biodiversity* TBID

Article ID: TBID 2184425

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Article: Three-dimensional (3D) modelling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

Journal: *Biodiversity* (TBID)

Article ID: TBID 2184425

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Submitted Corrections for article TBID 2184425

2 messages

TBID-production@journals.tandf.co.uk <cats@taylorandfrancis.com> Tue, Mar 7, 2023 at 12:50 PM
Reply-To: TBID-production@journals.tandf.co.uk
To: TBID-production@journals.tandf.co.uk, akhmad-t-m@fpk.unair.ac.id

Article: Three-dimensional (3D) modelling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

Journal: *Biodiversity* (TBID)

Article ID: TBID 2184425

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Reply-To: TBID-production@journals.tandf.co.uk
To: TBID-production@journals.tandf.co.uk, akhmad-t-m@fpk.unair.ac.id

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akhmad taufiq mukti <akhmad-t-m@fpk.unair.ac.id>

TBID_A_2184425- Author query

2 messages

Vithya Thirunavukarasou (Integra) <vithya.thirunavukarasou@integra.co.in> Fri, Mar 10, 2023 at 6:40 PM

To: "akhmad-t-m@fpk.unair.ac.id" <akhmad-t-m@fpk.unair.ac.id>
Cc: "TBID-production@journals.tandf.co.uk" <TBID-production@journals.tandf.co.uk>

Dear Akhmad Mukti,

My name is Vithya and I am the Production Assistant for Biodiversity. Thank you very much for sending in the corrections to your article, "Three-dimensional (3D) modelling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia". Thank you for submitting corrections for the article and the corrections are all amended in the final version.

Re-query: Unfortunately, we'll not be able to work of the updated version full manuscript submitted during the corrections review. Can you please mark the amendments to be carried out in a separate word document it would be great.

Looking forward to hearing back from you at the earliest.

Best regards,

Vithya Thirunavukarasou

Sr. Project Management

Integra Software Services

D : 0413-4212-026 Ext: 326| M : +91 9894597346

A : 100 Feet Road (ECR), Pakkamudiyanpet, Pondicherry 605 008, India

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17606K

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akhmad taufiq mukti <akhmad-t-m@fpk.unair.ac.id> Sun, Mar 12, 2023 at 9:20 PM
To: "Vithya Thirunavukarasou (Integra)" <vithya.thirunavukarasou@integra.co.in>

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Production Assistant for Biodiversity

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AUTHOR QUERIES

Q1 Please provide missing ORCIDs for the “Irawan, Andriyono, Muhsoni”.

Authors have mentioned in **ORCID** section of the article; page 13, lines 308-309.

Q2 The funding information “Grants of Penelitian Tesis Mahasiswa (PTM) with De” provided has been checked against the Open Funder Registry and we failed to find a match. Please confirm if the Funding section is accurate and also confirm the funder name “Grants of Penelitian Tesis Mahasiswa (PTM) with De”.

Authors have mentioned in **Acknowledgements** section of the article; page 12, lines 83-84 and in **Funding** section of the article; page 13, line 101.

Q3 The spelling of “Lange et al., 2020” has been changed to match the entry in the references list. Please provide revisions if this is incorrect.

Authors have revised spelling this reference and other references in text of the article.

Q4 The sense of the text “The 3D volume was measured by diving to a depth of 8 m and collecting 32 coral colonies” is not clear – how do diving and collecting produce volume measurements? Did you mean, perhaps, “The 3D volume was measured by collecting photographs of 32 coral colonies at a depth of 8 m”? Please edit to clarify the meaning. Please number all equations in the article.

Authors have revised sentence in **Materials and methods** of the article; page 5, lines 107-108.

Q5 Tables: Please spell out all abbreviations in each table, caption, and/or note.

Authors have revised sentence in **all Tables** of the article; pages 18-21, lines 418-419, 435, 449-450 and in **all Figures** of this article; pages 24-25, lines 502-503, 525.

Q6 The sense of the text “Calculating the volume of a 3D photo model is usually invisible and legible” is not clear. Did you mean, perhaps, “The volume of a 3D photo model is usually invisible and illegible”? Please edit to clarify the meaning.

Authors have revised sentence in **Results** of the article; page 9, line 204.

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Q8 Table 3: In the table caption, why is the word “weight” formatted in bold? Please either add an explanation for this, or remove the bold formatting.

Authors have revised sentence in Table 3 of the article; page 21, line 450.

Q9 Please provide a short biography of the author(s).

Authors have submitted a short biography of the all authors by system according to the affiliation as we have mentioned in the article.

Q10 The disclosure statement has been inserted. Please correct if this is inaccurate.

Authors have stated CLEAR on the disclosure statement and we have revised in **Disclosure statement** section of the article; page 13, line 297.

Q11 Please note that the ORCID for A. T. Mukti has been created from information provided through CATS. Please correct if this is inaccurate.

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Q12 please provide better quality for all figures.

Authors have revised quality of all figures as we have attached in the article; pages 23-25.

Best regards,
Akhmad Taufiq Mukti

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[Quoted text hidden]

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Three-dimensional (3D) modelling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

D. Irawan, A. T. Mukti, S. Andriyono and F. F. Muhsoni

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Three-dimensional (3D) modelling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

Q11 D. Irawan[a], A. T. Mukti[b], S. Andriyono[c] and F. F. Muhsoni[d]

Q1

[a]Master Program of Fisheries Sciences, Department of Aquaculture, Faculty of Fisheries and Marine, Universitas Airlangga, Surabaya, Indonesia; [b]Department of Aquaculture, Faculty of Fisheries and Marine, Universitas Airlangga, Surabaya, Indonesia; [c]Department of Marine, Faculty of Fisheries and Marine, Universitas Airlangga, Surabaya, Indonesia; [d]Study Program of Water Resource Management, Faculty of Agriculture, Universitas Trunojoyo Madura, Bangkalan, Indonesia

ABSTRACT

This study aimed to non-destructively measure the weight of massive (live) corals through three-dimensional (3D) modelling. The 3D models were constructed using the volumes and weight of massive (dead) corals. The study was conducted through photographs, 3D analysis, and weighing 32 massive (dead) coral samples. Volume and weight were modelled using linear and non-linear regressions, and their accuracy was tested using root mean square error (RMSE) and mean absolute percentage error (MAPE). This study showed that the weight of massive (live) corals could be measured using a 3D model of the massive (dead) coral's volume and the weight mainly through regression, polynomial, and geometric equations. The power/geometric equation is a more suitable approach for determining the actual value of coral weight. Linear regression obtained an average weight of 6.13 kg per plot. Three-dimensional modelling can be widely applied to measure the massive corals in the deep sea.

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Corals; Gili Labak Island; three-dimensional modelling; volume; weight

Introduction

The preservation of coral reef ecosystems is critical because many people in the twenty-first century will rely on these resources for food production, coastal protection, and the survival of their ecosystems (Kleypas et al. 2021). Coral reefs are among the most diverse and threatened ecosystems (Hoegh-Guldberg, Pendleton, and Kaup 2019). Therefore, monitoring their responses to various threats and disturbances is critical for management and conservation. Understanding the best methods for measuring changes in corals, ecosystems, and their functions is a challenge. An emerging method for exploring colony-scale growth patterns employs underwater photogrammetry to create digital models of coral colonies (Lange, Perry, and Cooper 2020). Acoustic methods are currently widely used to
Q3 detect the presence of underwater objects. These systems work exceptionally well.

Developing methodologies that allow the incorporation of three-dimensional (3D) metrics into coral reef monitoring is critical. One of the most commonly used metrics for assessing reef health is the proportion of live coral cover on reefs (Leujak and Ormond 2007). It is used as a proxy for calculating coral reef biomass and builds on the capabilities of most techniques used to evaluate linear or horizontal planar estimates. However, two-dimensional (2D) techniques alone are insufficient to estimate coral reef cover (Bamford and Forrester 2003), whereas 3D coral reef techniques provide valuable information on health (Dickens et al. 2011). The 3D surface and volume provide more accurate coral abundance statistics and allow for more accurate mapping of coral reef changes.

Manta tow, line intercept transect (LIT), point intercept transect (PIT), belt transect (BT), and quadratic transect (QT) are standard methods for researching coral reefs, depending on the purpose. The 3D modelling method is an advancement and modification of the underwater photo transect (UPT) method, which uses 3D photographs to identify coral species. Using 3D surface area and volume can provide more accurate metrics of coral abundance information and allows for more accurate capture of changes in coral reefs. This modelling is the most effective method for assessing coral reef damage and estimating carbon stocks. Comparison, photogrammetry, and 3D models offer a quick, simple, low-cost, and non-invasive method (Lange, Perry, and Cooper 2020). This study proposes a cost-effective and non-invasive method for accurate geometrical measurements of corals. Because it is

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impossible to obtain photographs of all coral surfaces and know the estimated weight of corals using a 3D approach, accuracy is highly dependent on the complexity of the coral reef. This study aimed to non-destructively measure the weight of massive (live) corals through 3D modelling.

Materials and methods

Research location

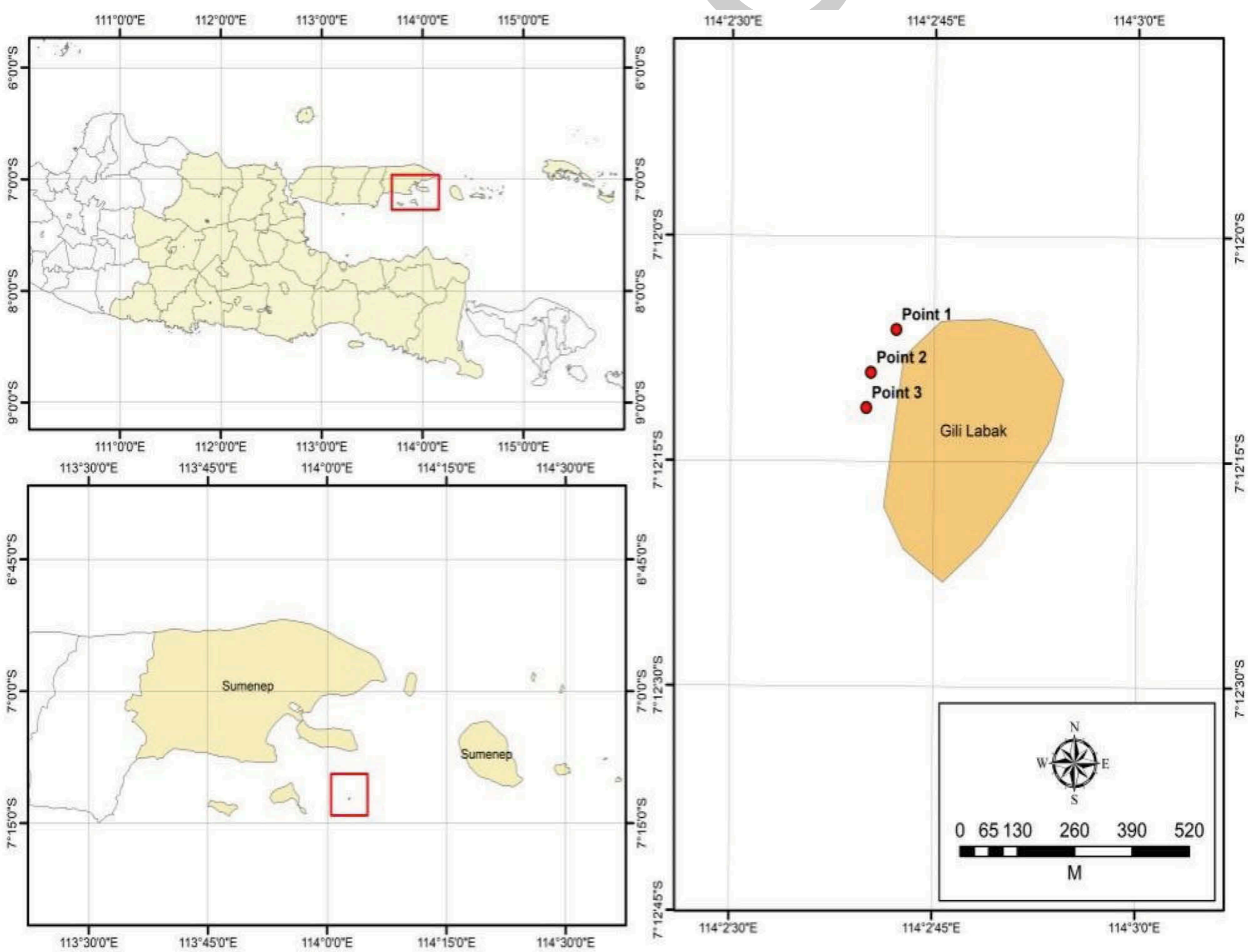
This study was conducted at a depth of 8–12 m on Gili Labak Island, Talango Sub-District, Sumenep Regency, Madura, East Java, Indonesia. A map of the study location is shown in Figure 1.

Sampling

A 3D model was created using 30 colonies of massive dead corals that were weighed and photographed for analysis in the Agisoft Metashape Professional (AMP) software. The volume and weight results were used to find linear and regression non-linear equations. Next, 30 coral samples were used for an accuracy test, and volume was measured in a pond using an Olympus TG-6 camera on a transect of 30 cm × 30 cm and in the field using a 50 cm × 50 cm frame for live coral (Figueira et al. 2015).

Three-dimensional measurement of massive corals

AMP software was also used to analyse the results of coral photographs. First, the image quality of underwater photographs was estimated using the image's sharpness, exposure, focus, resolution, and depth of field. The camera and build dense cloud (BDC) were then synced with the software and scaled with a scale. Third, a dense point cloud was created using depth information from each camera and a densification algorithm. Fourth, 3D nets were built. Creating texture is optional, but performing 3D measurement and analysis is not required. Planar projections by orthographic views were used to isolate a 'cleaned' coral colony



Q12

Figure 1. Map of the study location at Gili Labak Island, Talango Sub-District, Sumenep Regency, Madura, East Java, Indonesia.

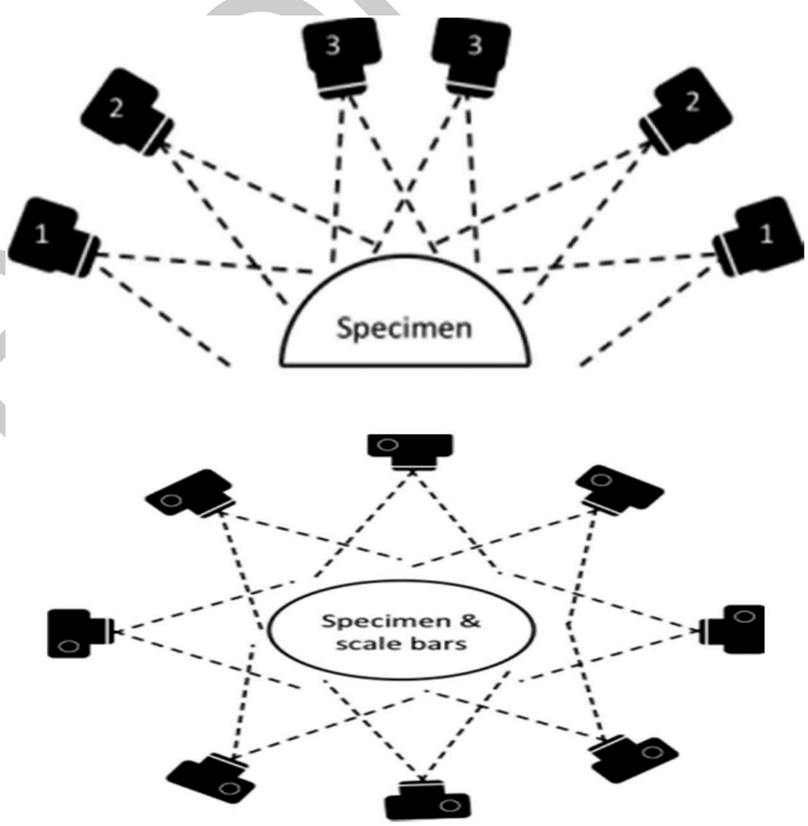
model from other reconstructed elements such as reef foundations, and AMP editing oriented all models. Exported models were used for quantitative analysis and volume calculations (Kabiri, Rezai, and Moradi 2020; de Oliveira et al. 2021).

Before taking the 3D photograph in the pond, the coral was weighed. These data were collected to create a model using linear and non-linear regression. Following that, 32 massive corals from the second sample were weighed for root mean square error (RMSE) and mean absolute percentage error (MAPE) tests. The 32 massive coral colonies were weighed to obtain the modelling test data. Then, the data were used to estimate the weight of massive live corals on Gili Labak Island. Data processing through 3D was carried out repeatedly.

Underwater camera

Coral colonies were photographed from every angle possible, including above and below. As shown in Figure 2, the camera was positioned at each object angle (Burns et al. 2015). The 3D volume was measured by diving to a depth of 8 m and collecting 32 coral
Q4 colonies. A schematic of the camera position is used to generate 3D images, as shown in Figure 2 (Ahmad, Jinah, and Saad 2020).

Massive corals were photographed in the pond using a 30 cm × 30 cm transect, while corals were photographed in the field using a 50 cm × 50 cm transect (Ahmad, Jinah, and Saad 2020). Continuous underwater photography from oblique planes and angles captured the entire colony surface (Figure 2), with 70–80% overlap (Bythell and Pan 2001; Burns et al. 2019). All photographs were uploaded to the AMP software, and the camera was calibrated using metadata-derived focus information. Furthermore, the photographs were aligned using an algorithm capable of detecting invariant features that overlap between consecutive photographs. A geometric projection matrix was created using invariant features and position, and the camera orientation for each photograph was determined according to Westoby et al. (2012). Extrinsic parameters calculated during the photo-alignment process were combined with intrinsic and focal parameters obtained from the metadata to create the 3D geometry from the 2D images (Stal et al. 2012). Bookmarks were used as a reference for all ground control points (GCPs), and the location of each marker in all photographs containing the GCP was reviewed and corrected. Values of x, y, and z for each GCP were entered into the software to



Q7 **Figure 2.** A schematic of the camera position used to produce three-dimensional images (Ahmad, Jinah, and Saad 2020).

optimize alignment and ensure the resulting model's accurate interior and exterior orientation.

The pattern of relationships between independent and dependent variables influencing the 3D weight and volume of coral reefs was determined using regression analysis (Scott, Hosmer, and Lemeshow 1991). This analysis was used to determine the conversion from volume to weight of corals in the field. Conversion from volume to weight of corals was obtained to the best value of non-linear regression. Regression analysis was divided into linear and non-linear regressions based on the relationship pattern. When the variables have a power/geometric relationship, the model is called a non-linear regression. When a non-linear regression model in parameters is differentiable, the result is always a function in parameters, as stated. The non-linear regression in parameters was calculated according to Scott, Hosmer, and Lemeshow (1991). Statistical analysis was performed on three regression and non-linear regression equation models – linear, polynomial, and power/geometric – based on 3D volume and weight photographs of massive (dead) corals.

RMSE test

An accuracy test was carried out to determine the best equation for estimating the volume and weight of corals. Using RMSE, an accuracy test was employed to determine the error value of the regression equation. Then, 3D volume photographs were compared to 3D weight photographs. The RMSE equations used were the following:

Q5

$$MSE = \sqrt{\frac{i}{n}\sum\nolimits_{i=1}^{n}\left(x_1 - y_1\right)^2}$$

$$RMSE(\%) = \frac{RMSE}{\acute{Y}} \times 100$$

where MSE = mean square error, RMSE = root mean square error, x_1 = 3D measurement result value, y_1 = 3D value prediction, and Ý = average 3D measurement results (Suprayogi 2014; Gurchiek et al. 2017).

MAPE test

MAPE was used to evaluate the estimation of the results and determine the accuracy of the estimated number and the realization rate. The following equation was used to calculate the value:

$$MAPE(\%) = \frac{\sum_{t=1}^{n}\frac{\left[A_{t-F_t}\right]}{At}}{n} \times 100$$

where MAPE = mean absolute percentage error, F_t = estimated value at time t, A_t = actual value at time t, and n = total data (t = 1, 2, . . ., n).

The MAPE test model's accuracy was measured according to three criteria: very accurate (MAPE < 5%), accurate (5% < MAPE < 10%), and inaccurate (MAPE > 10%) (Nabillah and Ranggadara 2020).

Data analysis

Three-dimensional photographs were taken in a small pond with 30 colonies to find linear and non-linear regression models, using 30 colonies for accuracy tests, and 32 samples of massive coral colonies for comparison (Fukunaga and Burns 2020). A digital elevation model (DEM) is a raster grid that references the subject surface's starting point. This modelling allows for the removal of objects from the surface, resulting in a 3D model with a smooth surface. If the DEM image does not appear during analysis, the volume results will not be displayed, and the analysis cannot be continued in the AMP software. The average number of photographs analysed in 3D for each coral colony was 93 to 98. The photographs were then analysed (Lange, Perry, and Cooper 2020) using AMP software (Kabiri, Rezai, and Moradi 2020; de Oliveira et al. 2021).

Results

We developed a 3D volume model of dead coral samples collected in the field. Dead coral samples were used to avoid causing harm to the coral ecosystem at the study site. Experiments with a frame binding point of 30 cm × 30 cm yielded photographs of the dead coral samples. The number was indicated as a binding point in the corner of the frame; the binding point's purpose is to serve as a GCP for 3D photo analysis. The results of the dead coral colony analysis are presented in Figure 3.

Next we analysed, using AMP software, the 3D images captured underwater from 30 massive (dead) coral colonies in a pond, which yielded 3D modelling volumes from the coral samples, with images captured of the entire coral surface. Each coral sample contains an average of 102 photographs. Table 1 shows the results of the RMSE control point analysis on the 3D photographs of corals in the pond.

The photographs were analysed in 3D using the AMP 1.7.4 software, and the RMSE control point value was calculated. Based on this analysis, the 3D photo error in the water (small pond) is less than 1 mm. The 3D photo analysis yielded an average RMSE (of corals in small ponds with an average of 102 photographs) X error of 0.29206 mm, Y error of 0.50167 mm, Z error of

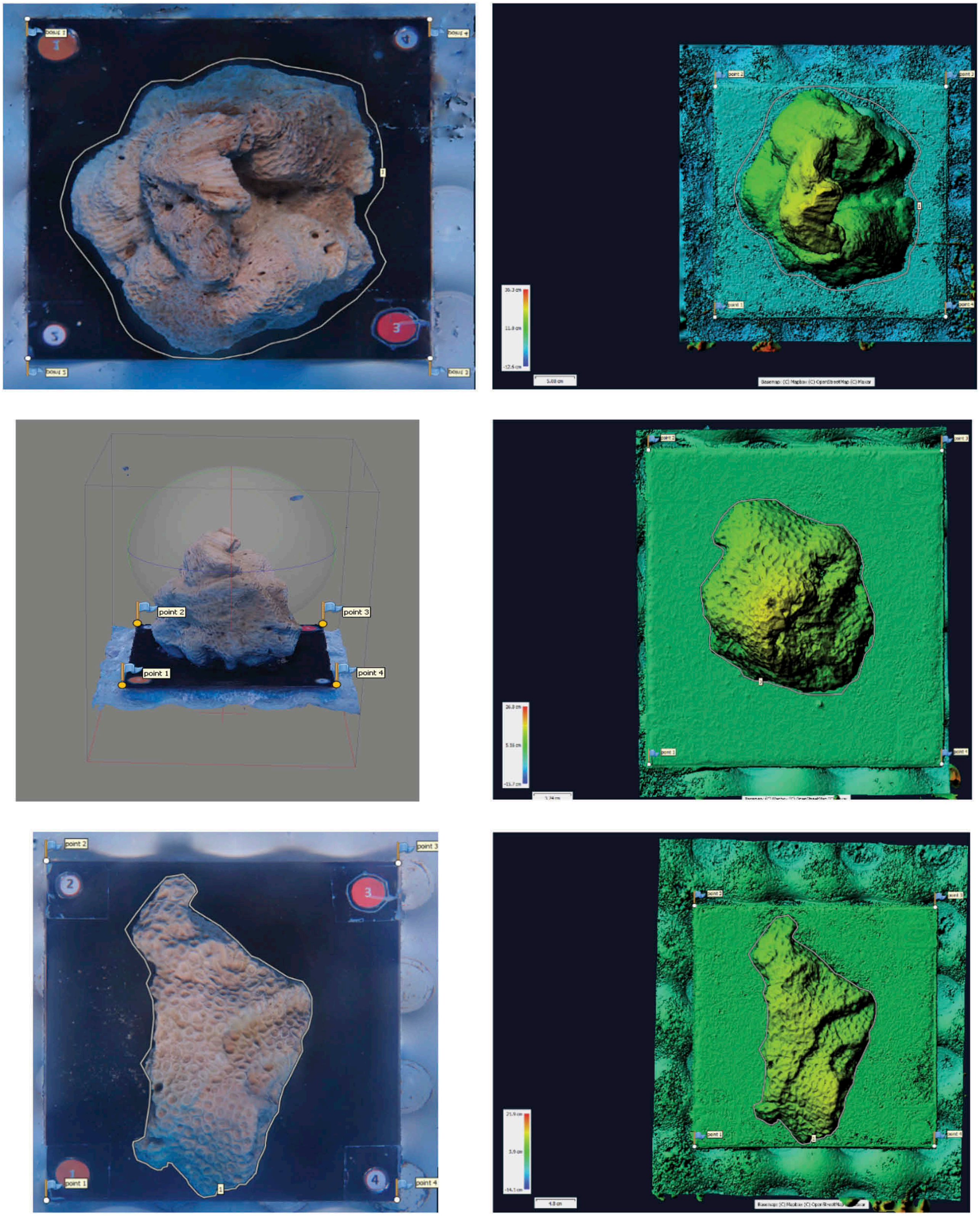


Figure 3. Results from the analysis, using Agisoft Metashape Professional (AMP) software, of the digital elevation model (DEM) and three-dimensional photographs of (dead) coral reefs.

Table 1. RMSE control points on the results of three-dimensional photo analysis in a small pond.

		RMSE				
Coral no.	No. of photos	X error (mm)	Y error (mm)	Z error (mm)	XY error (mm)	Total (mm)
1	97	0.55387	1.13955	0.77888	1.26703	1.48728
2	100	0.27418	0.18195	0.04357	0.32906	0.33193
3	96	0.86821	0.86821	2.64072	1.18693	2.89520
4	94	0.44546	0.40574	0.48895	0.60255	0.77597
5	102	0.16377	0.31121	0.01835	0.35167	0.35215
6	95	0.23989	0.26469	0.32463	0.35722	0.48270
7	89	0.01553	0.23047	0.15672	0.23099	0.27913
8	96	0.31492	0.28618	0.41279	0.42553	0.59285
9	110	0.26506	0.24065	0.15519	0.35801	0.39020
10	82	0.19772	0.57799	0.20527	0.60183	0.63587
11	89	0.06381	0.21831	0.12998	0.22744	0.26196
12	115	0.26025	0.42471	0.20647	0.49811	0.53921
13	114	0.26427	0.30750	0.20589	0.40546	0.45474
14	114	0.10470	0.33880	0.18488	0.35461	0.39992
15	95	0.15410	0.33145	0.23749	0.36552	0.43590
16	100	0.10025	0.36274	0.18387	0.37634	0.41886
17	102	0.05425	0.34436	0.16343	0.34861	0.38502
18	104	0.11650	0.13726	0.14757	0.18004	0.23279
19	93	0.30765	0.43068	0.06607	0.52928	0.53339
20	100	0.26892	0.42773	0.26986	0.50525	0.57280
21	110	0.08382	0.15316	0.26245	0.17459	0.31522
22	113	0.08055	0.18929	0.28779	0.20571	0.35375
23	114	0.16094	0.20679	0.04977	0.26204	0.26673
24	111	2.18783	5.24739	0.98116	5.68522	5.76926
25	110	0.14644	0.34430	0.68882	0.37415	0.52542
26	119	0.51075	0.23892	0.66404	0.56387	0.87115
27	94	0.10643	0.17073	0.18373	0.20119	0.27246
28	108	0.08465	0.21065	0.01163	0.22703	0.22733
29	101	0.07523	0.20130	0.13604	0.21490	0.25434
30	103	0.17461	0.25764	0.08381	0.31109	0.32218
Average	102	0.29206	0.50167	0.34566	0.59070	0.72119

Table 2. The volume of coral reefs from three-dimensional photo analysis by weight.

Analysis	Massive coral reefs	Test data
Linear	$y = 0.964x + 314.470$ $R^2 = 0.912$	RMSE = 284.50 g %RMSE = 20.50% MAPE = 27.43%
Polynomial	$y = 0.001x^2 + 1.235x + 49.448$ $R^2 = 0.915$	RMSE = 354.30 g %RMSE = 25.50% MAPE = 20.00%
Power/ geometric	$y = 2.451x^{o.898}$ $R^2 = 0.916$	RMSE = 251.20 g %RMSE = 18.10% MAPE = 19.17%

0.34566 mm, XY error of 0.59070, and total error of 0.72119 mm. The water's influence can affect the camera and distort the image. Table 2 displays the results of linear and non-linear regression analysis of weight and volume using AMP software.

Table 2 shows that the model with the best power/geometric accuracy resulted in $y = 2.451x^{o.898}$, $R^2 = 0.916$ with RMSE test of 251.20 g, %RMSE of 18.10%, and MAPE of 19.17%, while linear regression resulted in $y = 0.964x + 314.470$, $R^2 = 0.912$, RMSE of 284.50 g, %RMSE of 20.50%, and MAPE of 27.43%. Meanwhile, the polynomial resulted in y = 0.001x-$^{2\ +\ 1.235x\ +\ 49.448\ R2}$ = 0.915 with RMSE test of 354.30 g, %RMSE of 25.5%, and MAPE of 20.0%. Based on its orthographic projections, the coral colony orientation is utilized to calculate volume. On the other hand, growth orientation is influenced by environmental factors such as habitat complexity, slope, and light plane, potentially leading to estimation bias.

Coral samples were also weighed to calculate the mass of massive corals. All coral samples from the 3D photo volume and the weight of dead corals were used to obtain a model for the estimated live coral weight. The volume from 3D photographs and the weight of corals shown in Table 3 were used to construct a model using linear and non-linear regression equation approaches.

The volume of the coral could not be directly considered in the 3D photo analysis using AMP software because the coral has a complex shape and a concave

Q8 **Table 3.** The volume of three-dimensional (3D) photographs produced by AMP software and **weight** of coral conversion using a power/geometric model.

No.	Volume from the 3D photo analysis (cm^3)	Coral weight estimated using power/geometric model (g)	Genus of coral
1	2951	3191.71	*Favia*
2	3173	3406.42	*Favites*
3	6045	6075.19	*Pavona*
4	39,727	32,924.42	*Favia*
5	26,236	22,687.22	*Leptoseris*
6	5402	5491.86	*Favia*
7	5125	5238.42	*Coscinaraea*
8	8601	8337.39	*Leptoria*
9	1825	2073.42	*Favia*
10	2564	2813.35	*Caulastrea*
11	2093	2344.78	*Caulastrea*
12	3937	4134.27	*Pavona*
13	13,706	12,666.88	*Montastrea*
14	1703	1948.57	*Montastrea*
15	23,181	20,301.18	*Favites*
16	4388	4556.98	*Favia*
17	2223	2475.09	*Psammocora*
18	2983	3222.76	*Goniastrea*
19	4112	4298.86	*Favia*
20	384	511.77	*Montastrea*
21	10,421	9904.99	*Psammocora*
22	4016	4208.66	*Psammocora*
23	7715	7562.26	*Coscinaraea*
24	21	37.69	*Leptoseris*
25	7036	6962.07	*Psammocora*
26	14,529	13,347.55	*Psammocora*
27	226	318.00	*Euphyllia*
28	969	1174.64	*Psammocora*
29	471	614.73	*Montastrea*
30	255	354.40	*Porites*
31	253	351.90	*Porites*
32	2509	2759.12	*Favia*

bottom with small cavities. Calculating the volume of Q6 a 3D photo model is usually invisible and legible. As a result, a conversion is required to minimize errors when using a regression approach. The power/geometric conversion of the model from the initial data to the linear regression equation model is y = 2.451x0.898, R^2 = 0.916 with RMSE test of 251.20 g, %RMSE of 18.10%, and MAPE of 19.17%.

Data on corals

The results of the analysis of live coral colonies on Gili Labak Island can be seen in Figure 4. The modelling application and field data collection were tested on Gili Labak Island. Photographs were taken of a sample of 32 coral colonies by diving to depths ranging from 8 to 12 m. The iron frame used is 50 cm × 50 cm or 2500 cm^2, with a mark on each corner of the frame serving as a binding point for the photograph and making analysis easier in the AMP software. The results of the 3D analysis are shown in Table 3.

The model conversion from the initial data using the power/geometric equation model was $y = 2.451x^{0.898}$ with $R^2 = 0.916$. In Gili Labak Island, the average weight of coral volume produced is 6.13 kg per plot, and the total coral volume weight for the 32 plots is 169.92 kg, with a maximum value of 32.92 kg per plot and a minimum value of 0.04 kg per plot.

Discussion

The diversification of new methods in coral reef research is increasing. In this study, a new method was used to assist examiners who do not have direct experience in identifying coral in the sea, allowing novices to process data and identify coral on land without direct identification in the field. One advantage of the 3D method used in this study is the ability to obtain more controlled and verifiable data, and data on the volume of coral reefs that could not be obtained using previous methods. The work of Reichert et al. (2016) on scleractinian corals shows that the 3D method yields measurements of coral surface area and volume that are highly precise and easy to reproduce.

This study uses DEM results from AMP software to determine the volume of massive coral colonies and then models massive coral weight in Gili Labak Island, Sumenep, Madura. Three-dimensional modelling is the most effective data presentation method for describing coral reef damage. Acoustic methods are commonly used at present to detect the presence of underwater

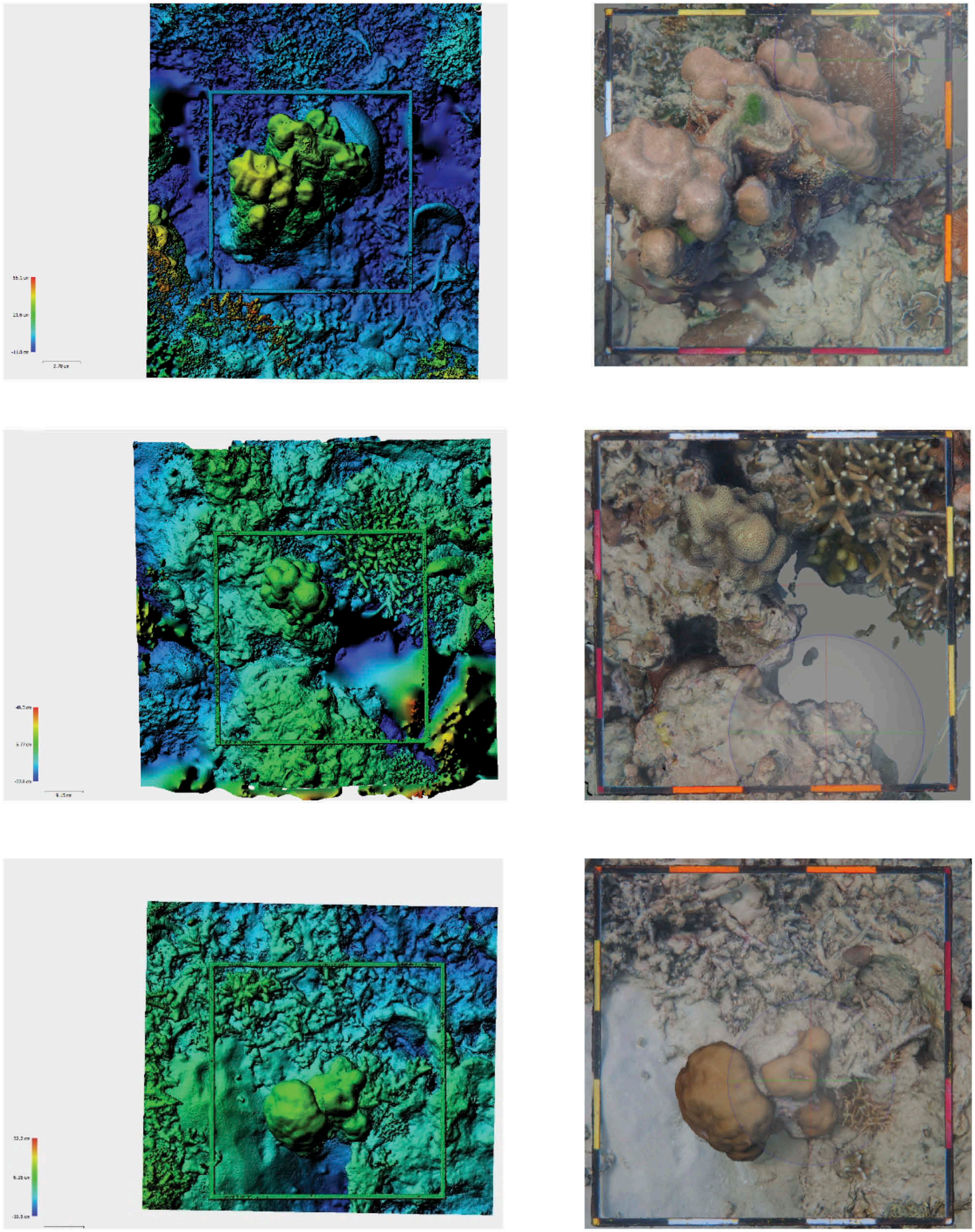


Figure 4. Results from the analysis of the digital elevation model (DEM) and three-dimensional photographs of coral reefs in Gili Labak Island, Sumenep, Madura.

objects. This system is beneficial for exploring the underwater environment (Kornder et al. 2021).

The emerging method of developing digital models of coral colonies using underwater photogrammetry provides a new and non-invasive way to examine colony-scale growth patterns and fill gaps in existing knowledge (Lange, Perry, and Cooper 2020). The main difficulty in coral reef ecology is estimating the abundance and composition of communities living in such complex ecosystems (Kornder et al. 2021). This study used technological advances to identify volumes in massive coral colonies using a 3D model. The advancement of photogrammetric technology has created a viable and practical method for exploring coral reefs (House et al. 2018). The structural parameters of reef surfaces and organisms have been shown to have relatively high accuracy when using photogrammetry in combination with underwater photogrammetry (Veal et al. 2010; Bryson et al. 2017).

Testing accuracy and precision are critical in any research, including underwater photogrammetry of corals. The accuracy and precision of the geometry obtained from the massive coral's 3D model were tested in this study. The results indicate that 3D measurement is an accurate quantitative study of the physiology and various sizes of coral colonies, and it can be done in situ. This technique could also be used to measure morphometrics of branching species, such as branch spacing, density, branch length, and branch angle. The 3D method precisely measures architectural complexity, topography, rugosity, volume, and other critical structural properties in ecosystems (Burns et al. 2015). This method reconstructs the 3D structure of corals and habitat-forming organisms at high resolution and accuracy by using a series of overlapping images taken from multiple perspectives (Bryson et al. 2017). Reichert et al. (2016) stated that the 3D method yields highly precise and reproducible measurements of the surface area and volume of corals.

This study also included RMSE test results, which had a value of 18.10% and a MAPE of 19.17%, whereas Hatcher et al. (2020) produced a relative RMSE of 0.013%. The present study produced a higher value of RMSE compared to Figueira et al. (2015), who obtained results of 10% from bottle coral measurements. The number of cameras used impacts the precision of results. In this study, only one camera was used; therefore, the RMSE value was higher and the results less precise than those of previous studies completed by Hatcher et al. (2020) and Figueira et al. (2015), who used five cameras to capture their underwater objects.

Photogrammetry was initially developed and applied in terrestrial settings, but it has since become a valuable tool for creating 3D models of bathymetry and underwater habitats. Because complete recordings of all surfaces are not possible, complex corals cannot be observed adequately with this model. This is a non-invasive method for obtaining precise geometric measurements of corals and other irregular underwater objects (Bythell and Pan 2001). The 3D method has many advantages but also several weaknesses, including longer analysis time and a requirement for more sophisticated software, high-spec computer devices, and special skills in underwater data collection through diving.

Conclusion

The massive corals in the deep sea can be identified and measured using non-disruptive 3D modelling. This study contributes to a growing body of knowledge revealing pathways that can be used to determine the carbon sequestered in coral reefs. This method is a non-invasive, cost-effective, and time-saving approach for obtaining accurate coral geometric measurements. Due to the difficulty in obtaining complete photographs of all surfaces, accuracy is highly dependent on the complexity of the coral reef and the number of cameras available for image capture.

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Author contributions

DI conceptualized the study, collected the materials, performed the experiment, measured parameters, analysed the data, and prepared the manuscript draft; ATM conceptualized the study, designed it, analysed the data, and edited and corrected the final manuscript; SA and proofread the manuscript draft and corrected the English grammar; FFM designed and corrected the manuscript draft. All authors read and approved the final manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors. Q10

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Based on requests for corrections to our article with ID **TBID #2184425 VOL 00, ISS 00** entitled "**Three-dimensional (3D) modelling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia**", we have submitted through the system. We also send the final article as we have adjusted it with corrections from the editor or article production team. We have mentioned **blue-color** the words or sentences in the article.

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Q1 Please provide missing ORCIDs for the "Irawan, Andriyono, Muhsoni".

Authors have mentioned in **ORCID** section of the article; page 13, lines 308-309.

Q2 The funding information "Grants of Penelitian Tesis Mahasiswa (PTM) with De" provided has been checked against the Open Funder Registry and we failed to find a match. Please confirm if the Funding section is accurate and also confirm the funder name "Grants of Penelitian Tesis Mahasiswa (PTM) with De".

Authors have mentioned in **Acknowledgements** section of the article; page 12, lines 83-84 and in **Funding** section of the article; page 13, line 101.

Q3 The spelling of "Lange et al., 2020" has been changed to match the entry in the references list. Please provide revisions if this is incorrect.

Authors have revised spelling this reference and other references in text of the article.

Q4 The sense of the text "The 3D volume was measured by diving to a depth of 8 m and collecting 32 coral colonies" is not clear – how do diving and collecting produce volume measurements? Did you mean, perhaps, "The 3D volume was measured by collecting photographs of 32 coral colonies at a depth of 8 m"? Please edit to clarify the meaning. Please number all equations in the article.

Authors have revised sentence in **Materials and methods** of the article; page 5, lines 107-108.

Q5 Tables: Please spell out all abbreviations in each table, caption, and/or note.

Authors have revised sentence in **all Tables** of the article; pages 18-21, lines 418-419, 435, 449-450 and in **all Figures** of this article; pages 24-25, lines 502-503, 525.

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Authors have revised sentence in **Results** of the article; page 9, line 204.

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Authors have revised sentence in Table 3 of the article; page 21, line 450.

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Authors have submitted a short biography of the all authors by system according to the affiliation as we have mentioned in the article.

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Authors have stated CLEAR on the disclosure statement and we have revised in **Disclosure statement** section of the article; page 13, line 297.

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Best regards,
Akhmad Taufiq Mukti

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[Quoted text hidden]

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Three-dimensional (3D) modelling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

D. Irawan, A. T. Mukti, S. Andriyono and F. F. Muhsoni

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Three-dimensional (3D) modelling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

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ABSTRACT

This study aimed to non-destructively measure the weight of massive (live) corals through three-dimensional (3D) modelling. The 3D models were constructed using the volumes and weight of massive (dead) corals. The study was conducted through photographs, 3D analysis, and weighing 32 massive (dead) coral samples. Volume and weight were modelled using linear and non-linear regressions, and their accuracy was tested using root mean square error (RMSE) and mean absolute percentage error (MAPE). This study showed that the weight of massive (live) corals could be measured using a 3D model of the massive (dead) coral's volume and the weight mainly through regression, polynomial, and geometric equations. The power/geometric equation is a more suitable approach for determining the actual value of coral weight. Linear regression obtained an average weight of 6.13 kg per plot. Three-dimensional modelling can be widely applied to measure the massive corals in the deep sea.

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Corals; Gili Labak Island; three-dimensional modelling; volume; weight

Introduction

The preservation of coral reef ecosystems is critical because many people in the twenty-first century will rely on these resources for food production, coastal protection, and the survival of their ecosystems (Kleypas et al. 2021). Coral reefs are among the most diverse and threatened ecosystems (Hoegh-Guldberg, Pendleton, and Kaup 2019). Therefore, monitoring their responses to various threats and disturbances is critical for management and conservation. Understanding the best methods for measuring changes in corals, ecosystems, and their functions is a challenge. An emerging method for exploring colony-scale growth patterns employs underwater photogrammetry to create digital models of coral colonies (Lange, Perry, and Cooper 2020). Acoustic methods are currently widely used to detect the presence of underwater objects. These systems work exceptionally well.

Developing methodologies that allow the incorporation of three-dimensional (3D) metrics into coral reef monitoring is critical. One of the most commonly used metrics for assessing reef health is the proportion of live coral cover on reefs (Leujak and Ormond 2007). It is used as a proxy for calculating coral reef biomass and builds on the capabilities of most techniques used to evaluate linear or horizontal planar estimates. However, two-dimensional (2D) techniques alone are insufficient to estimate coral reef cover (Bamford and Forrester 2003), whereas 3D coral reef techniques provide valuable information on health (Dickens et al. 2011). The 3D surface and volume provide more accurate coral abundance statistics and allow for more accurate mapping of coral reef changes.

Manta tow, line intercept transect (LIT), point intercept transect (PIT), belt transect (BT), and quadratic transect (QT) are standard methods for researching coral reefs, depending on the purpose. The 3D modelling method is an advancement and modification of the underwater photo transect (UPT) method, which uses 3D photographs to identify coral species. Using 3D surface area and volume can provide more accurate metrics of coral abundance information and allows for more accurate capture of changes in coral reefs. This modelling is the most effective method for assessing coral reef damage and estimating carbon stocks. Comparison, photogrammetry, and 3D models offer a quick, simple, low-cost, and non-invasive method (Lange, Perry, and Cooper 2020). This study proposes a cost-effective and non-invasive method for accurate geometrical measurements of corals. Because it is

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impossible to obtain photographs of all coral surfaces and know the estimated weight of corals using a 3D approach, accuracy is highly dependent on the complexity of the coral reef. This study aimed to non-destructively measure the weight of massive (live) corals through 3D modelling.

Materials and methods

Research location

This study was conducted at a depth of 8–12 m on Gili Labak Island, Talango Sub-District, Sumenep Regency, Madura, East Java, Indonesia. A map of the study location is shown in Figure 1.

Sampling

A 3D model was created using 30 colonies of massive dead corals that were weighed and photographed for analysis in the Agisoft Metashape Professional (AMP) software. The volume and weight results were used to find linear and regression non-linear equations. Next, 30 coral samples were used for an accuracy test, and volume was measured in a pond using an Olympus TG-6 camera on a transect of 30 cm × 30 cm and in the field using a 50 cm × 50 cm frame for live coral (Figueira et al. 2015).

Three-dimensional measurement of massive corals

AMP software was also used to analyse the results of coral photographs. First, the image quality of underwater photographs was estimated using the image's sharpness, exposure, focus, resolution, and depth of field. The camera and build dense cloud (BDC) were then synced with the software and scaled with a scale. Third, a dense point cloud was created using depth information from each camera and a densification algorithm. Fourth, 3D nets were built. Creating texture is optional, but performing 3D measurement and analysis is not required. Planar projections by orthographic views were used to isolate a 'cleaned' coral colony

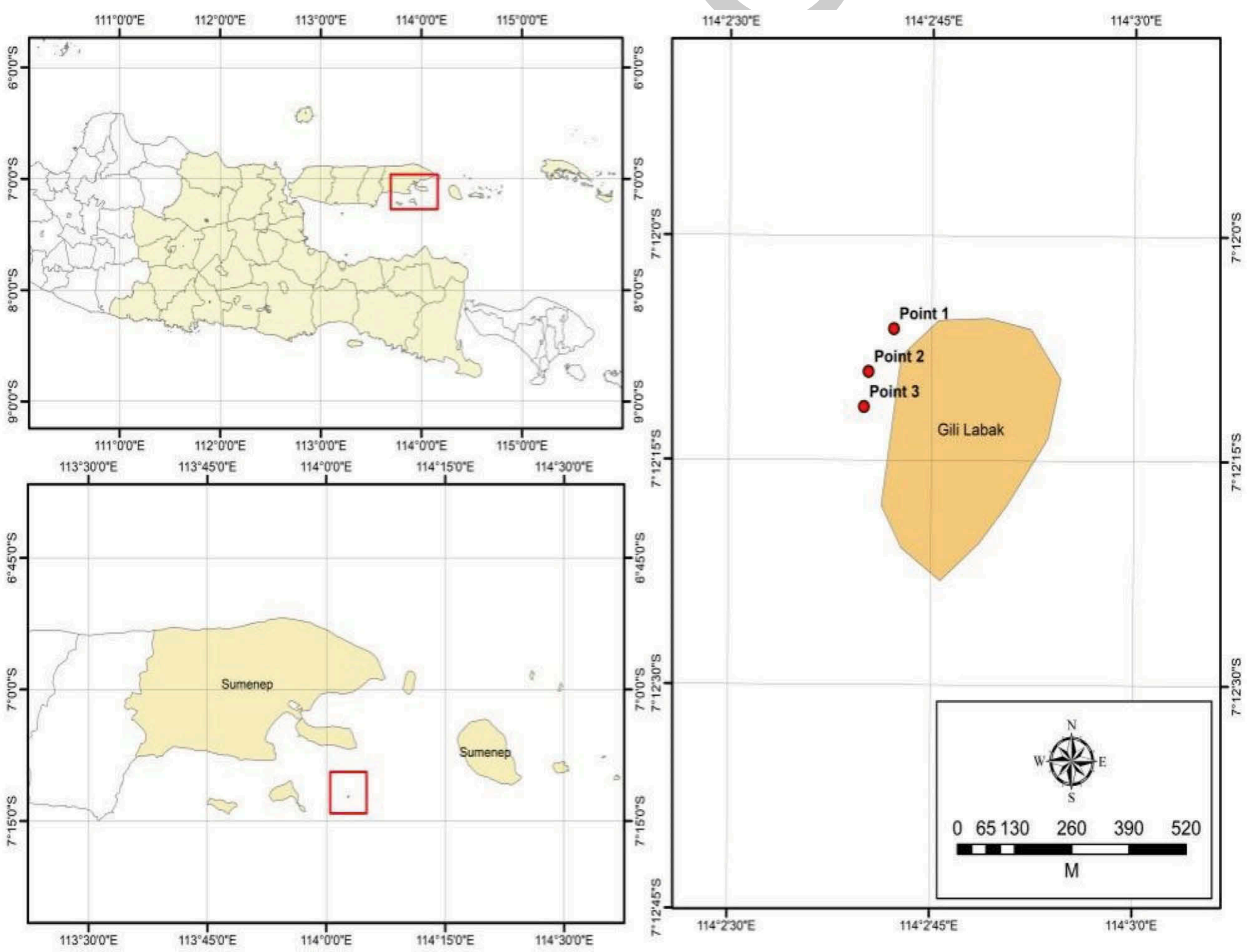

Figure 1. Map of the study location at Gili Labak Island, Talango Sub-District, Sumenep Regency, Madura, East Java, Indonesia.

model from other reconstructed elements such as reef foundations, and AMP editing oriented all models. Exported models were used for quantitative analysis and volume calculations (Kabiri, Rezai, and Moradi 2020; de Oliveira et al. 2021).

Before taking the 3D photograph in the pond, the coral was weighed. These data were collected to create a model using linear and non-linear regression. Following that, 32 massive corals from the second sample were weighed for root mean square error (RMSE) and mean absolute percentage error (MAPE) tests. The 32 massive coral colonies were weighed to obtain the modelling test data. Then, the data were used to estimate the weight of massive live corals on Gili Labak Island. Data processing through 3D was carried out repeatedly.

Underwater camera

Coral colonies were photographed from every angle possible, including above and below. As shown in Figure 2, the camera was positioned at each object angle (Burns et al. 2015). The 3D volume was measured by diving to a depth of 8 m and collecting 32 coral colonies. A schematic of the camera position is used to generate 3D images, as shown in Figure 2 (Ahmad, Jinah, and Saad 2020).

Massive corals were photographed in the pond using a 30 cm × 30 cm transect, while corals were photographed in the field using a 50 cm × 50 cm transect (Ahmad, Jinah, and Saad 2020). Continuous underwater photography from oblique planes and angles captured the entire colony surface (Figure 2), with 70–80% overlap (Bythell and Pan 2001; Burns et al. 2019). All photographs were uploaded to the AMP software, and the camera was calibrated using metadata-derived focus information. Furthermore, the photographs were aligned using an algorithm capable of detecting invariant features that overlap between consecutive photographs. A geometric projection matrix was created using invariant features and position, and the camera orientation for each photograph was determined according to Westoby et al. (2012). Extrinsic parameters calculated during the photo-alignment process were combined with intrinsic and focal parameters obtained from the metadata to create the 3D geometry from the 2D images (Stal et al. 2012). Bookmarks were used as a reference for all ground control points (GCPs), and the location of each marker in all photographs containing the GCP was reviewed and corrected. Values of x, y, and z for each GCP were entered into the software to

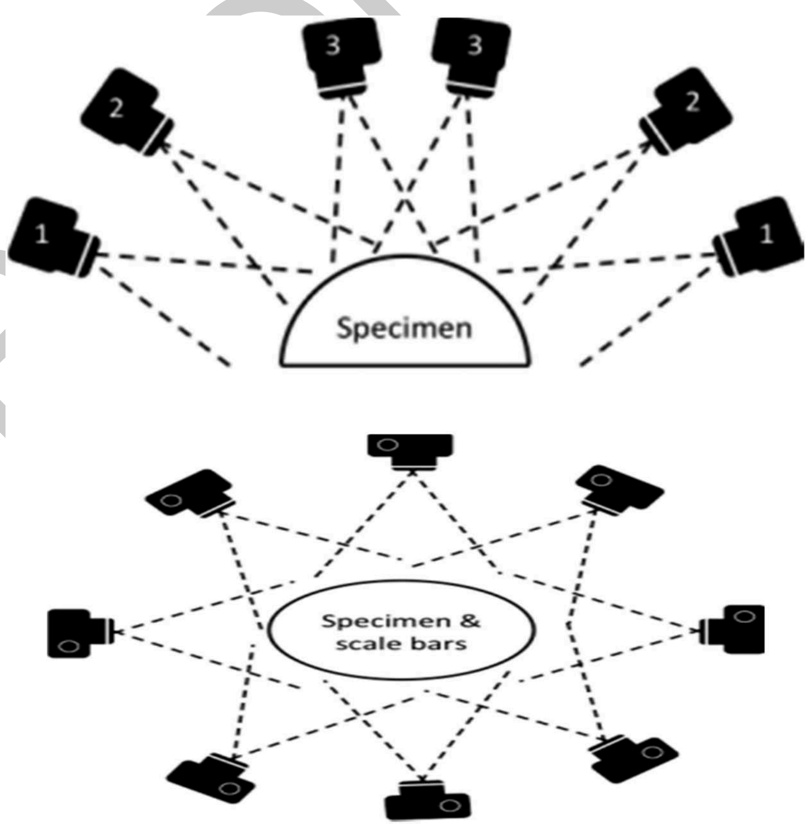

Figure 2. A schematic of the camera position used to produce three-dimensional images (Ahmad, Jinah, and Saad 2020).

optimize alignment and ensure the resulting model's accurate interior and exterior orientation.

The pattern of relationships between independent and dependent variables influencing the 3D weight and volume of coral reefs was determined using regression analysis (Scott, Hosmer, and Lemeshow 1991). This analysis was used to determine the conversion from volume to weight of corals in the field. Conversion from volume to weight of corals was obtained to the best value of non-linear regression. Regression analysis was divided into linear and non-linear regressions based on the relationship pattern. When the variables have a power/geometric relationship, the model is called a non-linear regression. When a non-linear regression model in parameters is differentiable, the result is always a function in parameters, as stated. The non-linear regression in parameters was calculated according to Scott, Hosmer, and Lemeshow (1991). Statistical analysis was performed on three regression and non-linear regression equation models – linear, polynomial, and power/geometric – based on 3D volume and weight photographs of massive (dead) corals.

RMSE test

An accuracy test was carried out to determine the best equation for estimating the volume and weight of corals. Using RMSE, an accuracy test was employed to determine the error value of the regression equation. Then, 3D volume photographs were compared to 3D weight photographs. The RMSE equations used were the following:

Q5

$$MSE = \sqrt{\frac{i}{n}\sum_{i=1}^{n}(x_1 - y_1)^2}$$

$$RMSE(\%) = \frac{RMSE}{\acute{Y}} \times 100$$

where MSE = mean square error, RMSE = root mean square error, x_1 = 3D measurement result value, y_1 = 3D value prediction, and Ý = average 3D measurement results (Suprayogi 2024; Gurchiek et al. 2017).

MAPE test

MAPE was used to evaluate the estimation of the results and determine the accuracy of the estimated number and the realization rate. The following equation was used to calculate the value:

$$MAPE(\%) = \frac{\sum_{t=1}^{n}\frac{[A_{t-F_t}]}{At}}{n} \times 100$$

where MAPE = mean absolute percentage error, F_t = estimated value at time t, A_t = actual value at time t, and n = total data (t = 1, 2, . . ., n).

The MAPE test model's accuracy was measured according to three criteria: very accurate (MAPE < 5%), accurate (5% < MAPE < 10%), and inaccurate (MAPE > 10%) (Nabillah and Ranggadara 2020).

Data analysis

Three-dimensional photographs were taken in a small pond with 30 colonies to find linear and non-linear regression models, using 30 colonies for accuracy tests, and 32 samples of massive coral colonies for comparison (Fukunaga and Burns 2020). A digital elevation model (DEM) is a raster grid that references the subject surface's starting point. This modelling allows for the removal of objects from the surface, resulting in a 3D model with a smooth surface. If the DEM image does not appear during analysis, the volume results will not be displayed, and the analysis cannot be continued in the AMP software. The average number of photographs analysed in 3D for each coral colony was 93 to 98. The photographs were then analysed (Lange, Perry, and Cooper 2020) using AMP software (Kabiri, Rezai, and Moradi 2020; de Oliveira et al. 2021).

Results

We developed a 3D volume model of dead coral samples collected in the field. Dead coral samples were used to avoid causing harm to the coral ecosystem at the study site. Experiments with a frame binding point of 30 cm × 30 cm yielded photographs of the dead coral samples. The number was indicated as a binding point in the corner of the frame; the binding point's purpose is to serve as a GCP for 3D photo analysis. The results of the dead coral colony analysis are presented in Figure 3.

Next we analysed, using AMP software, the 3D images captured underwater from 30 massive (dead) coral colonies in a pond, which yielded 3D modelling volumes from the coral samples, with images captured of the entire coral surface. Each coral sample contains an average of 102 photographs. Table 1 shows the results of the RMSE control point analysis on the 3D photographs of corals in the pond.

The photographs were analysed in 3D using the AMP 1.7.4 software, and the RMSE control point value was calculated. Based on this analysis, the 3D photo error in the water (small pond) is less than 1 mm. The 3D photo analysis yielded an average RMSE (of corals in small ponds with an average of 102 photographs) X error of 0.29206 mm, Y error of 0.50167 mm, Z error of

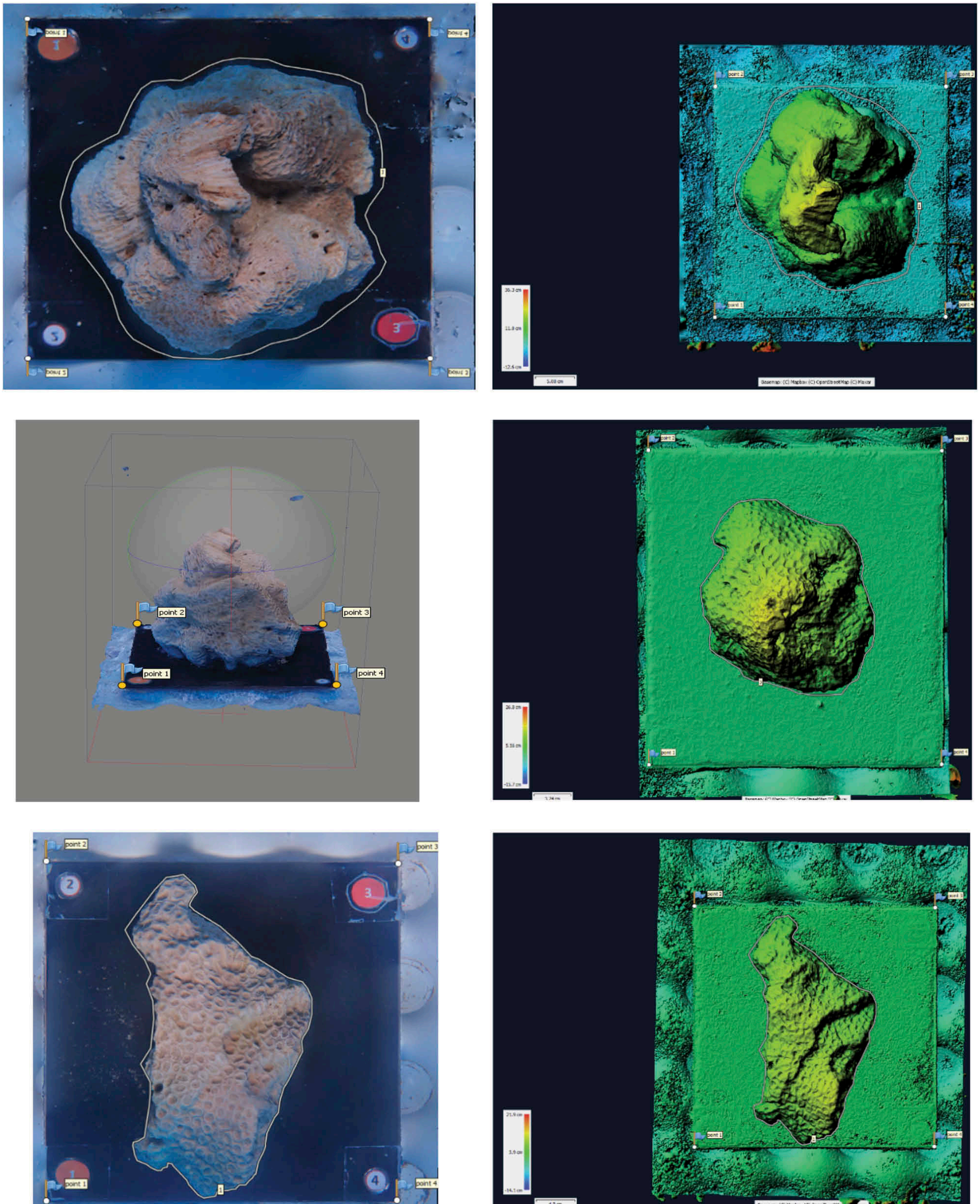

Figure 3. Results from the analysis using Agisoft Metashape Professional (AMP) software, of the digital elevation model (DEM) and three-dimensional photographs of (a–d) coral reefs.

Table 1. RMSE control points on the results of three-dimensional photo analysis in a small pond.

Coral no.	No. of photos	RMSE X error (mm)	Y error (mm)	Z error (mm)	XY error (mm)	Total (mm)
1	97	0.55387	1.13955	0.77888	1.26703	1.48728
2	100	0.27418	0.18195	0.04357	0.32906	0.33193
3	96	0.86821	0.86821	2.64072	1.18693	2.89520
4	94	0.44546	0.40574	0.48895	0.60255	0.77597
5	102	0.16377	0.31121	0.01835	0.35167	0.35215
6	95	0.23989	0.26469	0.32463	0.35722	0.48270
7	89	0.01553	0.23047	0.15672	0.23099	0.27913
8	96	0.31492	0.28618	0.41279	0.42553	0.59285
9	110	0.26506	0.24065	0.15519	0.35801	0.39020
10	82	0.19772	0.57799	0.20527	0.60183	0.63587
11	89	0.06381	0.21831	0.12998	0.22744	0.26196
12	115	0.26025	0.42471	0.20647	0.49811	0.53921
13	114	0.26427	0.30750	0.20589	0.40546	0.45474
14	114	0.10470	0.33880	0.18488	0.35461	0.39992
15	95	0.15410	0.33145	0.23749	0.36552	0.43590
16	100	0.10025	0.36274	0.18387	0.37634	0.41886
17	102	0.05425	0.34436	0.16343	0.34861	0.38502
18	104	0.11650	0.13726	0.14757	0.18004	0.23279
19	93	0.30765	0.43068	0.06607	0.52928	0.53339
20	100	0.26892	0.42773	0.26986	0.50525	0.57280
21	110	0.08382	0.15316	0.26245	0.17459	0.31522
22	113	0.08055	0.18929	0.28779	0.20571	0.35375
23	114	0.16094	0.20679	0.04977	0.26204	0.26673
24	111	2.18783	5.24739	0.98116	5.68522	5.76926
25	110	0.14644	0.34430	0.68882	0.37415	0.52542
26	119	0.51075	0.23892	0.66404	0.56387	0.87115
27	94	0.10643	0.17073	0.18373	0.20119	0.27246
28	108	0.08465	0.21065	0.01163	0.22703	0.22733
29	101	0.07523	0.20130	0.13604	0.21490	0.25434
30	103	0.17461	0.25764	0.08381	0.31109	0.32218
Average	102	0.29206	0.50167	0.34566	0.59070	0.72119

Table 2. The volume of coral reefs from three-dimensional photo analysis by weight.

Analysis	Massive coral reefs	Test data
Linear	$y = 0.964x + 314.470$ $R^2 = 0.912$	RMSE = 284.50 g %RMSE = 20.50% MAPE = 27.43%
Polynomial	$y = 0.001x^2 + 1.235x + 49.448$ $R^2 = 0.915$	RMSE = 354.30 g %RMSE = 25.50% MAPE = 20.00%
Power/ geometric	$y = 2.451x^{0.898}$ $R^2 = 0.916$	RMSE = 251.20 g %RMSE = 18.10% MAPE = 19.17%

0.34566 mm, XY error of 0.59070, and total error of 0.72119 mm. The water's influence can affect the camera and distort the image. Table 2 displays the results of linear and non-linear regression analysis of weight and volume using AMP software.

Table 2 shows that the model with the best power/ geometric accuracy resulted in $y = 2.451x^{0.898}$, $R^2 = 0.916$ with RMSE test of 251.20 g, %RMSE of 18.10%, and MAPE of 19.17%, while linear regression resulted in $y = 0.964x + 314.470$, $R^2 = 0.912$, RMSE of 284.50 g, %RMSE of 20.50%, and MAPE of 27.43%. Meanwhile, the polynomial resulted in y = 0.001x-$^{2\ +\ 1.235x\ +\ 49.448\ R2}$ = 0.915 with RMSE test of 354.30 g, %RMSE of 25.5%, and MAPE of 20.0%. Based on its orthographic projections, the coral colony orientation is utilized to calculate volume. On the other hand, growth orientation is influenced by environmental factors such as habitat complexity, slope, and light plane, potentially leading to estimation bias.

Coral samples were also weighed to calculate the mass of massive corals. All coral samples from the 3D photo volume and the weight of dead corals were used to obtain a model for the estimated live coral weight. The volume from 3D photographs and the weight of corals shown in Table 3 were used to construct a model using linear and non-linear regression equation approaches.

The volume of the coral could not be directly considered in the 3D photo analysis using AMP software because the coral has a complex shape and a concave

Table 3. The volume of three-dimensional (3D) photographs produced by AMP software and **weight** of coral conversion using a power/geometric model.

No.	Volume from the 3D photo analysis (cm^3)	Coral weight estimated using power/geometric model (g)	Genus of coral
1	2951	3191.71	*Favia*
2	3173	3406.42	*Favites*
3	6045	6075.19	*Pavona*
4	39,727	32,924.42	*Favia*
5	26,236	22,687.22	*Leptoseris*
6	5402	5491.86	*Favia*
7	5125	5238.42	*Coscinaraea*
8	8601	8337.39	*Leptoria*
9	1825	2073.42	*Favia*
10	2564	2813.35	*Caulastrea*
11	2093	2344.78	*Caulastrea*
12	3937	4134.27	*Pavona*
13	13,706	12,666.88	*Montastrea*
14	1703	1948.57	*Montastrea*
15	23,181	20,301.18	*Favites*
16	4388	4556.98	*Favia*
17	2223	2475.09	*Psammocora*
18	2983	3222.76	*Goniastrea*
19	4112	4298.86	*Favia*
20	384	511.77	*Montastrea*
21	10,421	9904.99	*Psammocora*
22	4016	4208.66	*Psammocora*
23	7715	7562.26	*Coscinaraea*
24	21	37.69	*Leptoseris*
25	7036	6962.07	*Psammocora*
26	14,529	13,347.55	*Psammocora*
27	226	318.00	*Euphyllia*
28	969	1174.64	*Psammocora*
29	471	614.73	*Montastrea*
30	255	354.40	*Porites*
31	253	351.90	*Porites*
32	2509	2759.12	*Favia*

bottom with small cavities. Calculating the volume of a 3D photo model is usually invisible and legible. As a result, a conversion is required to minimize errors when using a regression approach. The power/geometric conversion of the model from the initial data to the linear regression equation model is y = 2.451x0.898, R^2 = 0.916 with RMSE test of 251.20 g, %RMSE of 18.10%, and MAPE of 19.17%.

Data on corals

The results of the analysis of live coral colonies on Gili Labak Island can be seen in Figure 4. The modelling application and field data collection were tested on Gili Labak Island. Photographs were taken of a sample of 32 coral colonies by diving to depths ranging from 8 to 12 m. The iron frame used is 50 cm × 50 cm or 2500 cm^2, with a mark on each corner of the frame serving as a binding point for the photograph and making analysis easier in the AMP software. The results of the 3D analysis are shown in Table 3.

The model conversion from the initial data using the power/geometric equation model was $y = 2.451x^{0.898}$ with R^2 = 0.916. In Gili Labak Island, the average weight of coral volume produced is 6.13 kg per plot, and the total coral volume weight for the 32 plots is 169.92 kg, with a maximum value of 32.92 kg per plot and a minimum value of 0.04 kg per plot.

Discussion

The diversification of new methods in coral reef research is increasing. In this study, a new method was used to assist examiners who do not have direct experience in identifying coral in the sea, allowing novices to process data and identify coral on land without direct identification in the field. One advantage of the 3D method used in this study is the ability to obtain more controlled and verifiable data, and data on the volume of coral reefs that could not be obtained using previous methods. The work of Reichert et al. (2016) on scleractinian corals shows that the 3D method yields measurements of coral surface area and volume that are highly precise and easy to reproduce.

This study uses DEM results from AMP software to determine the volume of massive coral colonies and then models massive coral weight in Gili Labak Island, Sumenep, Madura. Three-dimensional modelling is the most effective data presentation method for describing coral reef damage. Acoustic methods are commonly used at present to detect the presence of underwater

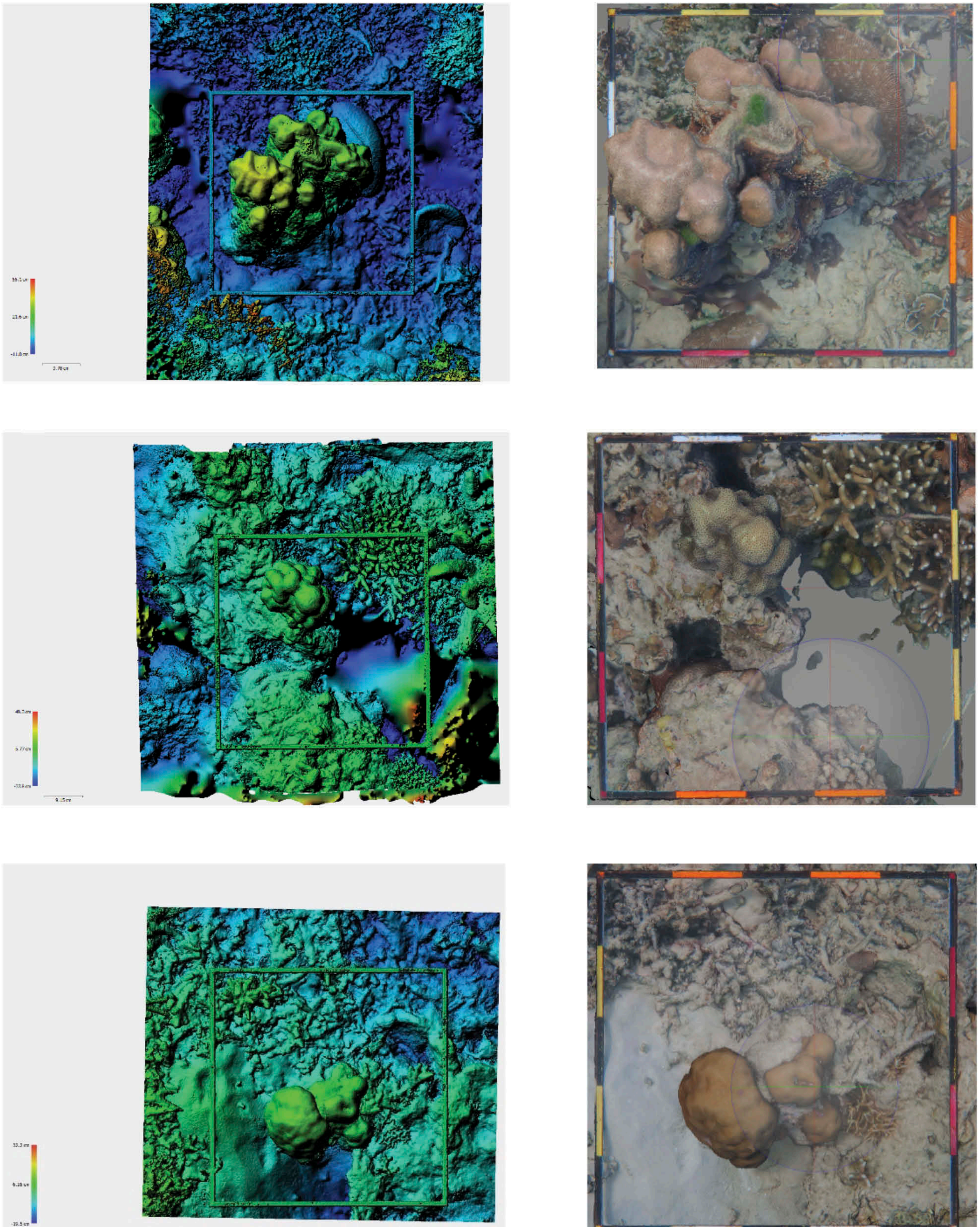

Figure [illegible] Results from the analysis of the digital elevation model (DEM) and three-dimensional photographs of coral reefs in Gili Labak Island, Sumenep, Madura.

objects. This system is beneficial for exploring the underwater environment (Kornder et al. 2021).

The emerging method of developing digital models of coral colonies using underwater photogrammetry provides a new and non-invasive way to examine colony-scale growth patterns and fill gaps in existing knowledge (Lange, Perry, and Cooper 2020). The main difficulty in coral reef ecology is estimating the abundance and composition of communities living in such complex ecosystems (Kornder et al. 2021). This study used technological advances to identify volumes in massive coral colonies using a 3D model. The advancement of photogrammetric technology has created a viable and practical method for exploring coral reefs (House et al. 2018). The structural parameters of reef surfaces and organisms have been shown to have relatively high accuracy when using photogrammetry in combination with underwater photogrammetry (Veal et al. 2010; Bryson et al. 2017).

Testing accuracy and precision are critical in any research, including underwater photogrammetry of corals. The accuracy and precision of the geometry obtained from the massive coral's 3D model were tested in this study. The results indicate that 3D measurement is an accurate quantitative study of the physiology and various sizes of coral colonies, and it can be done in situ. This technique could also be used to measure morphometrics of branching species, such as branch spacing, density, branch length, and branch angle. The 3D method precisely measures architectural complexity, topography, rugosity, volume, and other critical structural properties in ecosystems (Burns et al. 2015). This method reconstructs the 3D structure of corals and habitat-forming organisms at high resolution and accuracy by using a series of overlapping images taken from multiple perspectives (Bryson et al. 2017). Reichert et al. (2016) stated that the 3D method yields highly precise and reproducible measurements of the surface area and volume of corals.

This study also included RMSE test results, which had a value of 18.10% and a MAPE of 19.17%, whereas Hatcher et al. (2020) produced a relative RMSE of 0.013%. The present study produced a higher value of RMSE compared to Figueira et al. (2015), who obtained results of 10% from bottle coral measurements. The number of cameras used impacts the precision of results. In this study, only one camera was used; therefore, the RMSE value was higher and the results less precise than those of previous studies completed by Hatcher et al. (2020) and Figueira et al. (2015), who used five cameras to capture their underwater objects.

Photogrammetry was initially developed and applied in terrestrial settings, but it has since become a valuable tool for creating 3D models of bathymetry and underwater habitats. Because complete recordings of all surfaces are not possible, complex corals cannot be observed adequately with this model. This is a non-invasive method for obtaining precise geometric measurements of corals and other irregular underwater objects (Bythell and Pan 2001). The 3D method has many advantages but also several weaknesses, including longer analysis time and a requirement for more sophisticated software, high-spec computer devices, and special skills in underwater data collection through diving.

Conclusion

The massive corals in the deep sea can be identified and measured using non-disruptive 3D modelling. This study contributes to a growing body of knowledge revealing pathways that can be used to determine the carbon sequestered in coral reefs. This method is a non-invasive, cost-effective, and time-saving approach for obtaining accurate coral geometric measurements. Due to the difficulty in obtaining complete photographs of all surfaces, accuracy is highly dependent on the complexity of the coral reef and the number of cameras available for image capture.

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Author contributions

DI conceptualized the study, collected the materials, performed the experiment, measured parameters, analysed the data, and prepared the manuscript draft; ATM conceptualized the study, designed it, analysed the data, and edited and corrected the final manuscript; SA and proofread the manuscript draft and corrected the English grammar; FFM designed and corrected the manuscript draft. All authors read and approved the final manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

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To: TBID-production@journals.tandf.co.uk

Dear
Production Assistant for Biodiversity

Based on requests for corrections to our article with ID **TBID #2184425 VOL 00, ISS 00** entitled "**Three-dimensional (3D) modelling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia**", we have submitted through the system. We also send the final article as we have adjusted it with corrections from the editor or article production team. We have mentioned **blue-color** the words or sentences in the article.

AUTHOR QUERIES

Q1 Please provide missing ORCIDs for the "Irawan, Andriyono, Muhsoni".

Authors have mentioned in **ORCID** section of the article; page 13, lines 308-309.

Q2 The funding information "Grants of Penelitian Tesis Mahasiswa (PTM) with De" provided has been checked against the Open Funder Registry and we failed to find a match. Please confirm if the Funding section is accurate and also confirm the funder name "Grants of Penelitian Tesis Mahasiswa (PTM) with De".

Authors have mentioned in **Acknowledgements** section of the article; page 12, lines 83-84 and in **Funding** section of the article; page 13, line 101.

Q3 The spelling of "Lange et al., 2020" has been changed to match the entry in the references list. Please provide revisions if this is incorrect.

Authors have revised spelling this reference and other references in text of the article.

Q4 The sense of the text "The 3D volume was measured by diving to a depth of 8 m and collecting 32 coral colonies" is not clear – how do diving and collecting produce volume measurements? Did you mean, perhaps, "The 3D volume was measured by collecting photographs of 32 coral colonies at a depth of 8 m"? Please edit to clarify the meaning. Please number all equations in the article.

Authors have revised sentence in **Materials and methods** of the article; page 5, lines 107-108.

Q5 Tables: Please spell out all abbreviations in each table, caption, and/or note.

Authors have revised sentence in **all Tables** of the article; pages 18-21, lines 418-419, 435, 449-450 and in **all Figures** of this article; pages 24-25, lines 502-503, 525.

Q6 The sense of the text "Calculating the volume of a 3D photo model is usually invisible and legible" is not clear. Did you mean, perhaps, "The volume of a 3D photo model is usually invisible and illegible"? Please edit to clarify the meaning.

Authors have revised sentence in **Results** of the article; page 9, line 204.

Q7 If Figure 2 was taken from Ahmad et al. 2020, please confirm permission has been obtained to publish the image. Please provide details of the permission information, to be included in the figure caption.

Authors have deleted the figure of the article because there was no response from article authors of Ahmad et al. 2020 on the permission request.

Q8 Table 3: In the table caption, why is the word "weight" formatted in bold? Please either add an explanation for this, or remove the bold formatting.

Authors have revised sentence in Table 3 of the article; page 21, line 450.

Q9 Please provide a short biography of the author(s).

Authors have submitted a short biography of the all authors by system according to the affiliation as we have mentioned in the article.

Q10 The disclosure statement has been inserted. Please correct if this is inaccurate.

Authors have stated CLEAR on the disclosure statement and we have revised in **Disclosure statement** section of the article; page 13, line 297.

Q11 Please note that the ORCID for A. T. Mukti has been created from information provided through CATS. Please correct if this is inaccurate.

Authors have stated CLEAR on the ORCID as in **ORCID** section of the article; page 13, line 307.

Q12 please provide better quality for all figures.

Authors have revised quality of all figures as we have attached in the article; pages 23-25.

Best regards,
Akhmad Taufiq Mukti

Corresponding author

[Quoted text hidden]

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To: akhmad-t-m@fpk.unair.ac.id
Cc: vithya.thirunavukarasou@integra.co.in, shelley.barry@tandf.co.uk

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There seems to be a confusion in communication. You have sent us 4 files: one is the uncorrected PDF of your proofs; one is a list of corrections in Word referring to corrections you have made in the manuscript, but not explaining any of the corrections; one is a Word version of an updated version of your manuscript (with changes in blue); and the last is a PDF of your updated Word version.

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To: TBID-production@journals.tandf.co.uk

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Especially for Author Queries (Q12), we also attach all figure with better quality in this document.

Thank you very much.

Best regards,
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Your corrections have been received. Thank you. The corrections team will be in touch with you if they have any queries.

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3 messages

Barry, Shelley <Shelley.Barry@tandf.co.uk> Fri, Mar 17, 2023 at 7:13 PM
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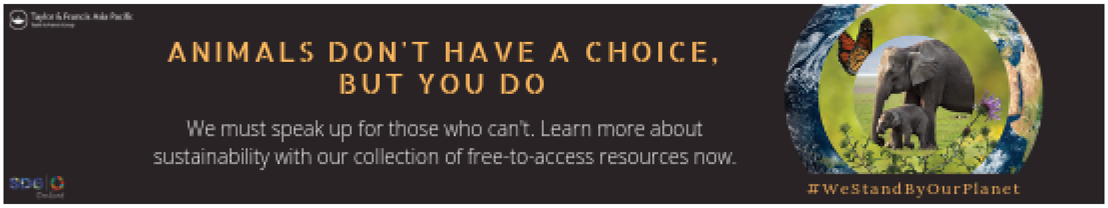

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To: "Barry, Shelley" <Shelley.Barry@tandf.co.uk>

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Thank you very much for the final correction of our article.

Best regards,
Akhmad Taufiq Mukti

Corresponding author
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Mon, Mar 20, 2023 at 4:05 PM

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We have included here the resubmitted final proofs of our article with a few corrections (in the attached PDF).
Thank you very much for the final correction of our article.

Best regards,
Akhmad Taufiq Mukti

Corresponding author
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Three-dimensional (3D) modelling to determine the weight of massive corals in Gili Labak Island, Sumenep, Madura, East Java, Indonesia

D. Irawan[a], A. T. Mukti [b], S. Andriyono [c] and F. F. Muhsoni [d]

[a]Master Program of Fisheries Sciences, Department of Aquaculture, Faculty of Fisheries and Marine, Universitas Airlangga, Surabaya, Indonesia; [b]Department of Aquaculture, Faculty of Fisheries and Marine, Universitas Airlangga, Surabaya, Indonesia; [c]Department of Marine, Faculty of Fisheries and Marine, Universitas Airlangga, Surabaya, Indonesia; [d]Study Program of Water Resource Management, Faculty of Agriculture, Universitas Trunojoyo Madura, Bangkalan, Indonesia

ABSTRACT
This study aimed to non-destructively measure the weight of massive (live) corals through three-dimensional (3D) modelling. The 3D models were constructed using the volumes and weight of massive (dead) corals. The study was conducted through photographs, 3D analysis, and weighing 32 massive (dead) coral samples. Volume and weight were modelled using linear and non-linear regressions, and their accuracy was tested using root mean square error (RMSE) and mean absolute percentage error (MAPE). This study showed that the weight of massive (live) corals could be measured using a 3D model of the massive (dead) coral's volume and the weight mainly through regression, polynomial, and geometric equations. The power/geometric equation is a more suitable approach for determining the actual value of coral weight. Linear regression obtained an average weight of 6.13 kg per plot. Three-dimensional modelling can be widely applied to measure the massive corals in the deep sea.

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KEYWORDS
Corals; Gili Labak Island; three-dimensional modelling; volume; weight

Introduction

The preservation of coral reef ecosystems is critical because many people in the twenty-first century will rely on these resources for food production, coastal protection, and the survival of their ecosystems (Kleypas et al. 2021). Coral reefs are among the most diverse and threatened ecosystems (Hoegh-Guldberg, Pendleton, and Kaup 2019). Therefore, monitoring their responses to various threats and disturbances is critical for management and conservation. Understanding the best methods for measuring changes in corals, ecosystems, and their functions is a challenge. An emerging method for exploring colony-scale growth patterns employs underwater photogrammetry to create digital models of coral colonies (Lange, Perry, and Cooper 2020). Acoustic methods are currently widely used to detect the presence of underwater objects. These systems work exceptionally well.

Developing methodologies that allow the incorporation of three-dimensional (3D) metrics into coral reef monitoring is critical. One of the most commonly used metrics for assessing reef health is the proportion of live coral cover on reefs (Leujak and Ormond 2007). It is used as a proxy for calculating coral reef biomass and builds on the capabilities of most techniques used to evaluate linear or horizontal planar estimates. However, two-dimensional (2D) techniques alone are insufficient to estimate coral reef cover (Bamford and Forrester 2003), whereas 3D coral reef techniques provide valuable information on health (Dickens et al. 2011). The 3D surface and volume provide more accurate coral abundance statistics and allow for more accurate mapping of coral reef changes.

Manta tow, line intercept transect (LIT), point intercept transect (PIT), belt transect (BT), and quadratic transect (QT) are standard methods for researching coral reefs, depending on the purpose. The 3D modelling method is an advancement and modification of the underwater photo transect (UPT) method, which uses 3D photographs to identify coral species. Using 3D surface area and volume can provide more accurate metrics of coral abundance information and allows for more accurate capture of changes in coral reefs. This modelling is the most effective method for assessing coral reef damage and estimating carbon stocks. Comparison, photogrammetry, and 3D models offer a quick, simple, low-cost, and non-invasive method (Lange, Perry, and Cooper 2020). This study proposes a cost-effective and non-invasive method for accurate geometrical measurements of corals. Because it is impossible to obtain

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photographs of all coral surfaces and know the estimated weight of corals using a 3D approach, accuracy is highly dependent on the complexity of the coral reef. This study aimed to non-destructively measure the weight of massive (live) corals through 3D modelling.

Materials and methods

Research location

This study was conducted at a depth of 8–12 m on Gili Labak Island, Talango Sub-District, Sumenep Regency, Madura, East Java, Indonesia. A map of the study location is shown in Figure 1.

Sampling

A 3D model was created using 30 colonies of massive dead corals that were weighed and photographed for analysis in the Agisoft Metashape Professional (AMP) software. The volume and weight results were used to find linear and regression non-linear equations. Next, 30 coral samples were used for an accuracy test, and volume was measured in a pond using an Olympus TG-6 camera on a transect of 30 cm × 30 cm and in the field using a 50 cm × 50 cm frame for live coral (Figueira et al. 2015).

Three-dimensional measurement of massive corals

AMP software was also used to analyse the results of coral photographs. First, the image quality of underwater photographs was estimated using the image's sharpness, exposure, focus, resolution, and depth of field. The camera and build dense cloud (BDC) were then synced with the software and scaled with a scale. Third, a dense point cloud was created using depth information from each camera and a densification algorithm. Fourth, 3D nets were built. Creating texture is optional, but performing 3D measurement and analysis is not required. Planar projections by orthographic views were used to isolate a 'cleaned' coral colony model from other reconstructed elements such as reef foundations, and AMP editing oriented all models. Exported models were used for quantitative analysis and volume calculations (Kabiri, Rezai, and Moradi 2020; de Oliveira et al. 2021).

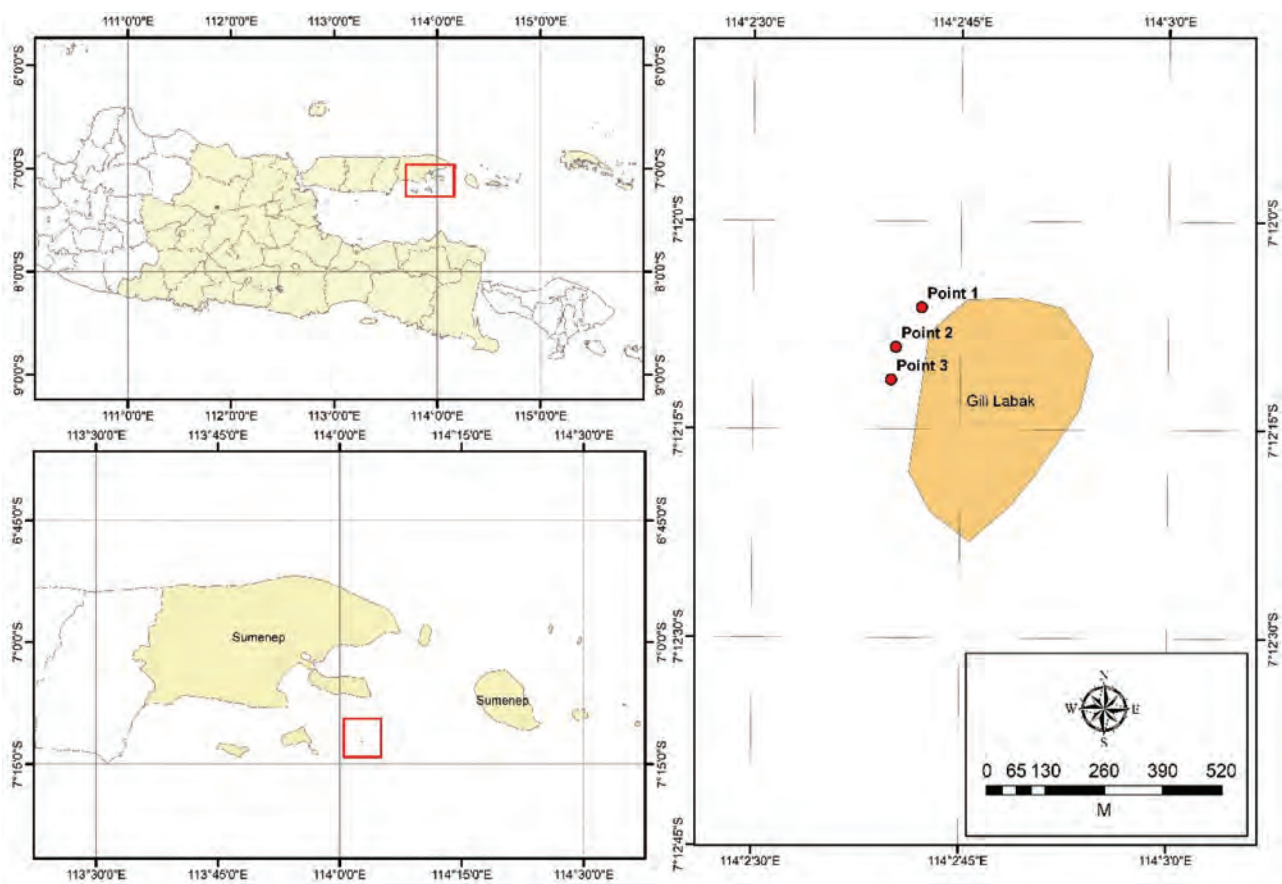

Figure 1. Map of the study location at Gili Labak Island, Talango Sub-District, Sumenep Regency, Madura, East Java, Indonesia.

Before taking the 3D photograph in the pond, the coral was weighed. These data were collected to create a model using linear and non-linear regression. Following that, 32 massive corals from the second sample were weighed for root mean square error (RMSE) and mean absolute percentage error (MAPE) tests. The 32 massive coral colonies were weighed to obtain the modelling test data. Then, the data were used to estimate the weight of massive live corals on Gili Labak Island. Data processing through 3D was carried out repeatedly.

Underwater camera

Coral colonies were photographed from every angle possible, including above and below. The camera was positioned at each object angle (Burns et al. 2015). The 3D volume was measured by collecting photographs of 32 coral colonies at a depth of 8 m. A schematic of the camera position is used to generate 3D images, as illustrated by Ahmad, Jinah, and Saad (2020).

Massive corals were photographed in the pond using a 30 cm × 30 cm transect, while corals were photographed in the field using a 50 cm × 50 cm transect (Ahmad, Jinah, and Saad 2020). Continuous underwater photography from oblique planes and angles captured the entire colony surface, with 70–80% overlap (Bythell and Pan 2001; Burns et al. 2019). All photographs were uploaded to the AMP software, and the camera was calibrated using metadata-derived focus information. Furthermore, the photographs were aligned using an algorithm capable of detecting invariant features that overlap between consecutive photographs. A geometric projection matrix was created using invariant features and position, and the camera orientation for each photograph was determined according to Westoby et al. (2012). Extrinsic parameters calculated during the photo-alignment process were combined with intrinsic and focal parameters obtained from the metadata to create the 3D geometry from the 2D images (Stal et al. 2012). Bookmarks were used as a reference for all ground control points (GCPs), and the location of each marker in all photographs containing the GCP was reviewed and corrected. Values of x, y, and z for each GCP were entered into the software to optimize alignment and ensure the resulting model's accurate interior and exterior orientation.

The pattern of relationships between independent and dependent variables influencing the 3D weight and volume of coral reefs was determined using regression analysis (Scott, Hosmer, and Lemeshow 1991). This analysis was used to determine the conversion from volume to weight of corals in the field. Conversion from volume to weight of corals was obtained to the best value of non-linear regression. Regression analysis was divided into linear and non-linear regressions based on the relationship pattern. When the variables have a power/geometric relationship, the model is called a non-linear regression. When a non-linear regression model in parameters is differentiable, the result is always a function in parameters, as stated. The non-linear regression in parameters was calculated according to Scott, Hosmer, and Lemeshow (1991). Statistical analysis was performed on three regression and non-linear regression equation models – linear, polynomial, and power/geometric – based on 3D volume and weight photographs of massive (dead) corals.

RMSE test

An accuracy test was carried out to determine the best equation for estimating the volume and weight of corals. Using RMSE, an accuracy test was employed to determine the error value of the regression equation. Then, 3D volume photographs were compared to 3D weight photographs. The RMSE equations used were the following:

$$\mathrm{RMSE} = \sqrt{\frac{i}{n}\sum\nolimits_{i=1}^{n}(x_1 - y_1)^2}$$

$$\mathrm{RMSE}(\%) = \frac{RMSE}{\acute{Y}} \times 100$$

where MSE = mean square error, RMSE = root mean square error, x_1 = 3D measurement result value, y_1 = 3D value prediction, and $\acute{Y}$ = average 3D measurement results (Suprayogi, Trimaijon, and Mahyudin 2014; Gurchiek et al. 2017).

MAPE test

MAPE was used to evaluate the estimation of the results and determine the accuracy of the estimated number and the realization rate. The following equation was used to calculate the value:

$$\mathrm{MAPE}(\%) = \frac{\sum\nolimits_{t=1}^{n}\frac{[A_{t-F_t}]}{At}}{n} \times 100$$

where MAPE = mean absolute percentage error, F_t = estimated value at time t, A_t = actual value at time t, and n = total data (t = 1, 2, . . ., n).

The MAPE test model's accuracy was measured according to three criteria: very accurate (MAPE <

5%), accurate (5% < MAPE < 10%), and inaccurate (MAPE > 10%) (Nabillah and Ranggadara 2020).

Data analysis

Three-dimensional photographs were taken in a small pond with 30 colonies to find linear and non-linear regression models, using 30 colonies for accuracy tests, and 32 samples of massive coral colonies for comparison (Fukunaga and Burns 2020). A digital elevation model (DEM) is a raster grid that references the subject surface's starting point. This modelling allows for the removal of objects from the surface, resulting in a 3D model with a smooth surface. If the DEM image does not appear during analysis, the volume results will not be displayed, and the analysis cannot be continued in the AMP software. The average number of photographs analysed in 3D for each coral colony was 93 to 98. The photographs were then analysed (Lange, Perry, and Cooper 2020) using AMP software (Kabiri, Rezai, and Moradi 2020; de Oliveira et al. 2021).

Results

We developed a 3D volume model of dead coral samples collected in the field. Dead coral samples were used to avoid causing harm to the coral ecosystem at the study site. Experiments with a frame binding point of 30 cm × 30 cm yielded photographs of the dead coral samples. The number was indicated as a binding point in the corner of the frame; the binding point's purpose is to serve as a GCP for 3D photo analysis. The results of the dead coral colony analysis are presented in Figure 2.

Next we analysed, using AMP software, the 3D images captured underwater from 30 massive (dead) coral colonies in a pond, which yielded 3D modelling volumes from the coral samples, with images captured of the entire coral surface. Each coral sample contains an average of 102 photographs. Table 1 shows the results of the RMSE control point analysis on the 3D photographs of corals in the pond.

The photographs were analysed in 3D using the AMP 1.7.4 software, and the RMSE control point value was calculated. Based on this analysis, the 3D photo error in the water (small pond) is less than 1 mm. The 3D photo analysis yielded an average RMSE (of corals in small ponds with an average of 102 photographs) X error of 0.29206 mm, Y error of 0.50167 mm, Z error of 0.34566 mm, XY error of 0.59070, and total error of 0.72119 mm. The water's influence can affect the camera and distort the image. Table 2 displays the results of linear and non-linear regression analysis of weight and volume using AMP software.

Table 2 shows that the model with the best power/geometric accuracy resulted in $y = 2.451x^{0.898}$, $R^2 = 0.916$ with RMSE test of 251.20 g, %RMSE of 18.10%, and MAPE of 19.17%, while linear regression resulted in $y = 0.964x + 314.470$, $R^2 = 0.912$, RMSE of 284.50 g, %RMSE of 20.50%, and MAPE of 27.43%. Meanwhile, the polynomial resulted in $y = 0.001x^{2} + 1.235x + 49.448$ $R^2 = 0.915$ with RMSE test of 354.30 g, %RMSE of 25.5%, and MAPE of 20.0%. Based on its orthographic projections, the coral colony orientation is utilized to calculate volume. On the other hand, growth orientation is influenced by environmental factors such as habitat complexity, slope, and light plane, potentially leading to estimation bias.

Coral samples were also weighed to calculate the mass of massive corals. All coral samples from the 3D photo volume and the weight of dead corals were used to obtain a model for the estimated live coral weight. The volume from 3D photographs and the weight of corals shown in Table 3 were used to construct a model using linear and non-linear regression equation approaches.

The volume of the coral could not be directly considered in the 3D photo analysis using AMP software because the coral has a complex shape and a concave bottom with small cavities. The volume of a 3D photo model is usually invisible and illegible. As a result, a conversion is required to minimize errors when using a regression approach. The power/geometric conversion of the model from the initial data to the linear regression equation model is y = 2.451x0.898, $R^2 = 0.916$ with RMSE test of 251.20 g, %RMSE of 18.10%, and MAPE of 19.17%.

Data on corals

The results of the analysis of live coral colonies on Gili Labak Island can be seen in Figure 3. The modelling application and field data collection were tested on Gili Labak Island. Photographs were taken of a sample of 32 coral colonies by diving to depths ranging from 8 to 12 m. The iron frame used is 50 cm × 50 cm or 2500 cm^2, with a mark on each corner of the frame serving as a binding point for the photograph and making analysis easier in the AMP software. The results of the 3D analysis are shown in Table 3.

The model conversion from the initial data using the power/geometric equation model was $y = 2.451x^{0.898}$ with $R^2 = 0.916$. In Gili Labak Island, the average weight of coral volume produced is 6.13 kg per plot, and the total coral volume weight for the 32 plots is 169.92 kg, with a maximum value of 32.92 kg per plot and a minimum value of 0.04 kg per plot.

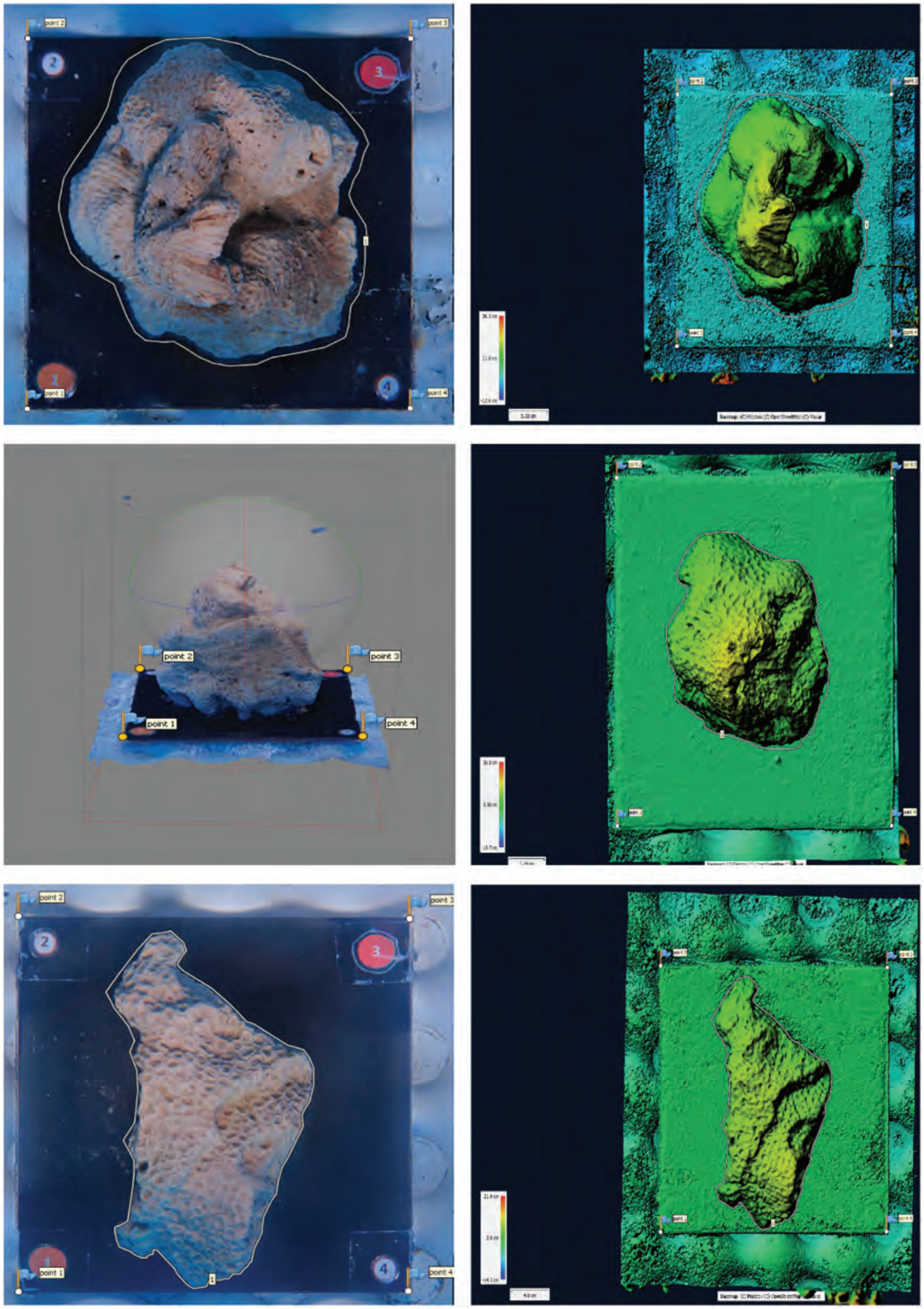

Figure 2. Results from the analysis, using Agisoft Metashape Professional (AMP) software, of the digital elevation model (DEM) and three-dimensional photographs of massive (dead) corals.

Table 1. Root mean square error (RMSE) control points on the results of three-dimensional (3D) photographs analysis in a small pond.

Coral no.	No. of photos	Root mean square error (RMSE)				
		X error (mm)	Y error (mm)	Z error (mm)	XY error (mm)	Total (mm)
1	97	0.55387	1.13955	0.77888	1.26703	1.48728
2	100	0.27418	0.18195	0.04357	0.32906	0.33193
3	96	0.86821	0.86821	2.64072	1.18693	2.89520
4	94	0.44546	0.40574	0.48895	0.60255	0.77597
5	102	0.16377	0.31121	0.01835	0.35167	0.35215
6	95	0.23989	0.26469	0.32463	0.35722	0.48270
7	89	0.01553	0.23047	0.15672	0.23099	0.27913
8	96	0.31492	0.28618	0.41279	0.42553	0.59285
9	110	0.26506	0.24065	0.15519	0.35801	0.39020
10	82	0.19772	0.57799	0.20527	0.60183	0.63587
11	89	0.06381	0.21831	0.12998	0.22744	0.26196
12	115	0.26025	0.42471	0.20647	0.49811	0.53921
13	114	0.26427	0.30750	0.20589	0.40546	0.45474
14	114	0.10470	0.33880	0.18488	0.35461	0.39992
15	95	0.15410	0.33145	0.23749	0.36552	0.43590
16	100	0.10025	0.36274	0.18387	0.37634	0.41886
17	102	0.05425	0.34436	0.16343	0.34861	0.38502
18	104	0.11650	0.13726	0.14757	0.18004	0.23279
19	93	0.30765	0.43068	0.06607	0.52928	0.53339
20	100	0.26892	0.42773	0.26986	0.50525	0.57280
21	110	0.08382	0.15316	0.26245	0.17459	0.31522
22	113	0.08055	0.18929	0.28779	0.20571	0.35375
23	114	0.16094	0.20679	0.04977	0.26204	0.26673
24	111	2.18783	5.24739	0.98116	5.68522	5.76926
25	110	0.14644	0.34430	0.68882	0.37415	0.52542
26	119	0.51075	0.23892	0.66404	0.56387	0.87115
27	94	0.10643	0.17073	0.18373	0.20119	0.27246
28	108	0.08465	0.21065	0.01163	0.22703	0.22733
29	101	0.07523	0.20130	0.13604	0.21490	0.25434
30	103	0.17461	0.25764	0.08381	0.31109	0.32218
Average	102	0.29206	0.50167	0.34566	0.59070	0.72119

Table 2. The volume of corals from three-dimensional (3D) photographs analysis by weight.

Analysis	Massive coral reefs	Test data
Linear	$y = 0.964x + 314.470$ $R^2 = 0.912$	RMSE = 284.50 g %RMSE = 20.50% MAPE = 27.43%
Polynomial	$y = 0.001x^2 + 1.235x + 49.448$ $R^2 = 0.915$	RMSE = 354.30 g %RMSE = 25.50% MAPE = 20.00%
Power/ geometric	$y = 2.451x^{0.898}$ $R^2 = 0.916$	RMSE = 251.20 g %RMSE = 18.10% MAPE = 19.17%

RMSE = root mean square error, MAPE = mean absolute percentage error.

Discussion

The diversification of new methods in coral reef research is increasing. In this study, a new method was used to assist examiners who do not have direct experience in identifying coral in the sea, allowing novices to process data and identify coral on land without direct identification in the field. One advantage of the 3D method used in this study is the ability to obtain more controlled and verifiable data, and data on the volume of coral reefs that could not be obtained using previous methods. The work of Reichert et al. (2016) on scleractinian corals shows that the 3D method yields measurements of coral surface area and volume that are highly precise and easy to reproduce.

This study uses DEM results from AMP software to determine the volume of massive coral colonies and then models massive coral weight in Gili Labak Island, Sumenep, Madura. Three-dimensional modelling is the most effective data presentation method for describing coral reef damage. Acoustic methods are commonly used at present to detect the presence of underwater objects. This system is beneficial for exploring the underwater environment (Kornder et al. 2021).

The emerging method of developing digital models of coral colonies using underwater photogrammetry provides a new and non-invasive way to examine colony-scale growth patterns and fill gaps in existing knowledge (Lange, Perry, and Cooper 2020). The main difficulty in coral reef ecology is estimating the

Table 3. The volume of three-dimensional (3D) photographs produced by Agisoft Metashape Professional (AMP) software and weight of coral conversion using a power/geometric model.

No.	Volume from the 3D photo analysis (cm^3)	Coral weight estimated using power/geometric model (g)	Genus of coral
1	2951	3191.71	*Favia*
2	3173	3406.42	*Favites*
3	6045	6075.19	*Pavona*
4	39,727	32,924.42	*Favia*
5	26,236	22,687.22	*Leptoseris*
6	5402	5491.86	*Favia*
7	5125	5238.42	*Coscinaraea*
8	8601	8337.39	*Leptoria*
9	1825	2073.42	*Favia*
10	2564	2813.35	*Caulastrea*
11	2093	2344.78	*Caulastrea*
12	3937	4134.27	*Pavona*
13	13,706	12,666.88	*Montastrea*
14	1703	1948.57	*Montastrea*
15	23,181	20,301.18	*Favites*
16	4388	4556.98	*Favia*
17	2223	2475.09	*Psammocora*
18	2983	3222.76	*Goniastrea*
19	4112	4298.86	*Favia*
20	384	511.77	*Montastrea*
21	10,421	9904.99	*Psammocora*
22	4016	4208.66	*Psammocora*
23	7715	7562.26	*Coscinaraea*
24	21	37.69	*Leptoseris*
25	7036	6962.07	*Psammocora*
26	14,529	13,347.55	*Psammocora*
27	226	318.00	*Euphyllia*
28	969	1174.64	*Psammocora*
29	471	614.73	*Montastrea*
30	255	354.40	*Porites*
31	253	351.90	*Porites*
32	2509	2759.12	*Favia*

abundance and composition of communities living in such complex ecosystems (Kornder et al. 2021). This study used technological advances to identify volumes in massive coral colonies using a 3D model. The advancement of photogrammetric technology has created a viable and practical method for exploring coral reefs (House et al. 2018). The structural parameters of reef surfaces and organisms have been shown to have relatively high accuracy when using photogrammetry in combination with underwater photogrammetry (Veal et al. 2010; Bryson et al. 2017).

Testing accuracy and precision are critical in any research, including underwater photogrammetry of corals. The accuracy and precision of the geometry obtained from the massive coral's 3D model were tested in this study. The results indicate that 3D measurement is an accurate quantitative study of the physiology and various sizes of coral colonies, and it can be done in situ. This technique could also be used to measure morphometrics of branching species, such as branch spacing, density, branch length, and branch angle. The 3D method precisely measures architectural complexity, topography, rugosity, volume, and other critical structural properties in ecosystems (Burns et al. 2015). This method reconstructs the 3D structure of corals and habitat-forming organisms at high resolution and accuracy by using a series of overlapping images taken from multiple perspectives (Bryson et al. 2017). Reichert et al. (2016) stated that the 3D method yields highly precise and reproducible measurements of the surface area and volume of corals.

This study also included RMSE test results, which had a value of 18.10% and a MAPE of 19.17%, whereas Hatcher et al. (2020) produced a relative RMSE of 0.013%. The present study produced a higher value of RMSE compared to Figueira et al. (2015), who obtained results of 10% from bottle coral measurements. The number of cameras used impacts the precision of results. In this study, only one camera was used; therefore, the RMSE value was higher and the results less precise than those of previous studies completed by Hatcher et al. (2020) and Figueira et al. (2015), who used five cameras to capture their underwater objects.

Photogrammetry was initially developed and applied in terrestrial settings, but it has since become a valuable tool for creating 3D models of bathymetry and underwater habitats. Because complete recordings of all surfaces are not possible, complex corals cannot be observed adequately with this model. This is a non-invasive method for obtaining precise geometric

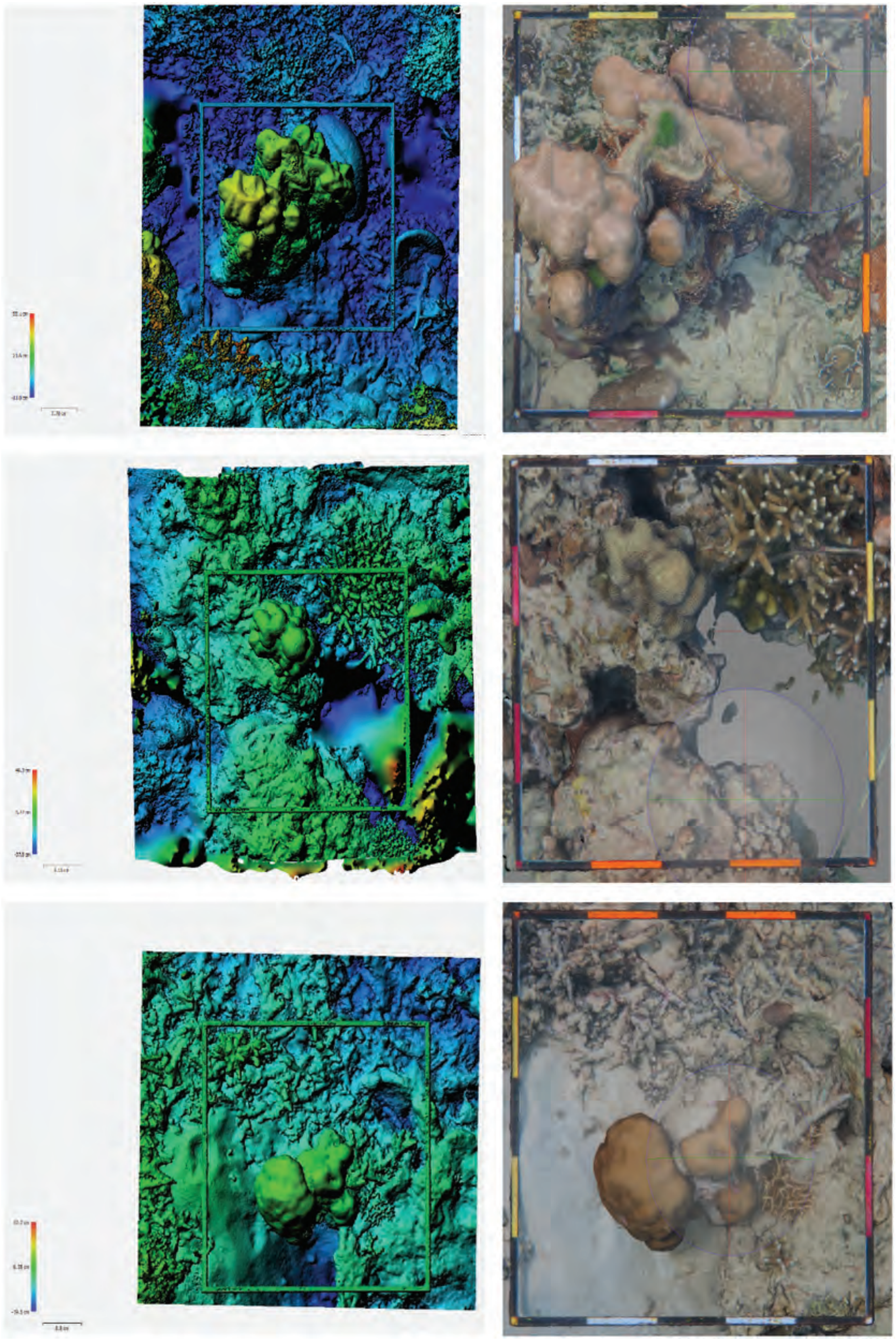

Figure 3. Results from the analysis of the digital elevation model (DEM) and three-dimensional photographs of corals in Gili Labak Island, Sumenep, Madura.

measurements of corals and other irregular underwater objects (Bythell and Pan 2001). The 3D method has many advantages but also several weaknesses, including longer analysis time and a requirement for more sophisticated software, high-spec computer devices, and special skills in underwater data collection through diving.

Conclusion

The massive corals in the deep sea can be identified and measured using non-disruptive 3D modelling. This study contributes to a growing body of knowledge revealing pathways that can be used to determine the carbon sequestered in coral reefs. This method is a non-invasive, cost-effective, and time-saving approach for obtaining accurate coral geometric measurements. Due to the difficulty in obtaining complete photographs of all surfaces, accuracy is highly dependent on the complexity of the coral reef and the number of cameras available for image capture.

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Author contributions

DI conceptualized the study, collected the materials, performed the experiment, measured parameters, analysed the data, and prepared the manuscript draft; ATM conceptualized the study, designed it, analysed the data, and edited and corrected the final manuscript; SA and proofread the manuscript draft and corrected the English grammar; FFM designed and corrected the manuscript draft. All authors read and approved the final manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Q3 The spelling of "Lange et al., 2020" has been changed to match the entry in the references list. Please provide revisions if this is incorrect.

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Q4 The sense of the text "The 3D volume was measured by diving to a depth of 8 m and collecting 32 coral colonies" is not clear – how do diving and collecting produce volume measurements? Did you mean, perhaps, "The 3D volume was measured by collecting photographs of 32 coral colonies at a depth of 8 m"? Please edit to clarify the meaning. Please number all equations in the article.

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Q5 Tables: Please spell out all abbreviations in each table, caption, and/or note.

Authors have revised sentence in **all Tables** of the article; pages 18-21, lines 418-419, 435, 449-450 and in **all Figures** of this article; pages 24-25, lines 502-503, 525.

Q6 The sense of the text “Calculating the volume of a 3D photo model is usually invisible and legible” is not clear. Did you mean, perhaps, “The volume of a 3D photo model is usually invisible and illegible”? Please edit to clarify the meaning.

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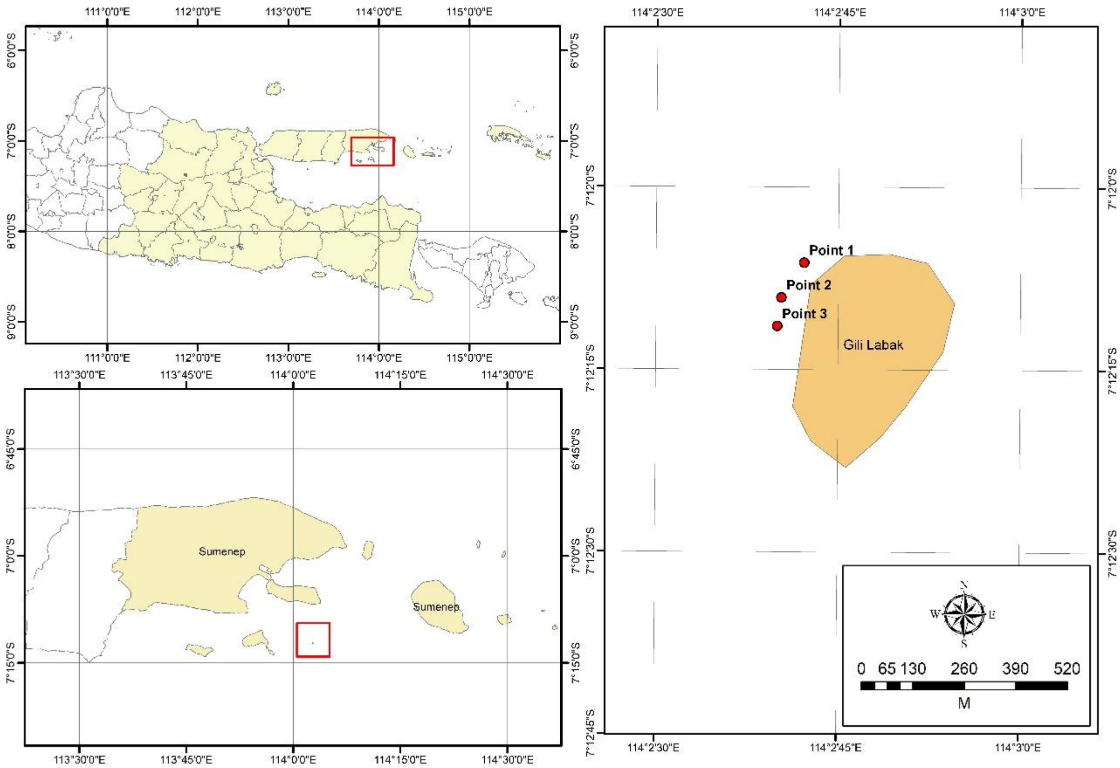

Figure 1. Map of the study location at Gili Labak Island, Talango Sub-District, Sumenep Regency, Madura, East Java, Indonesia.

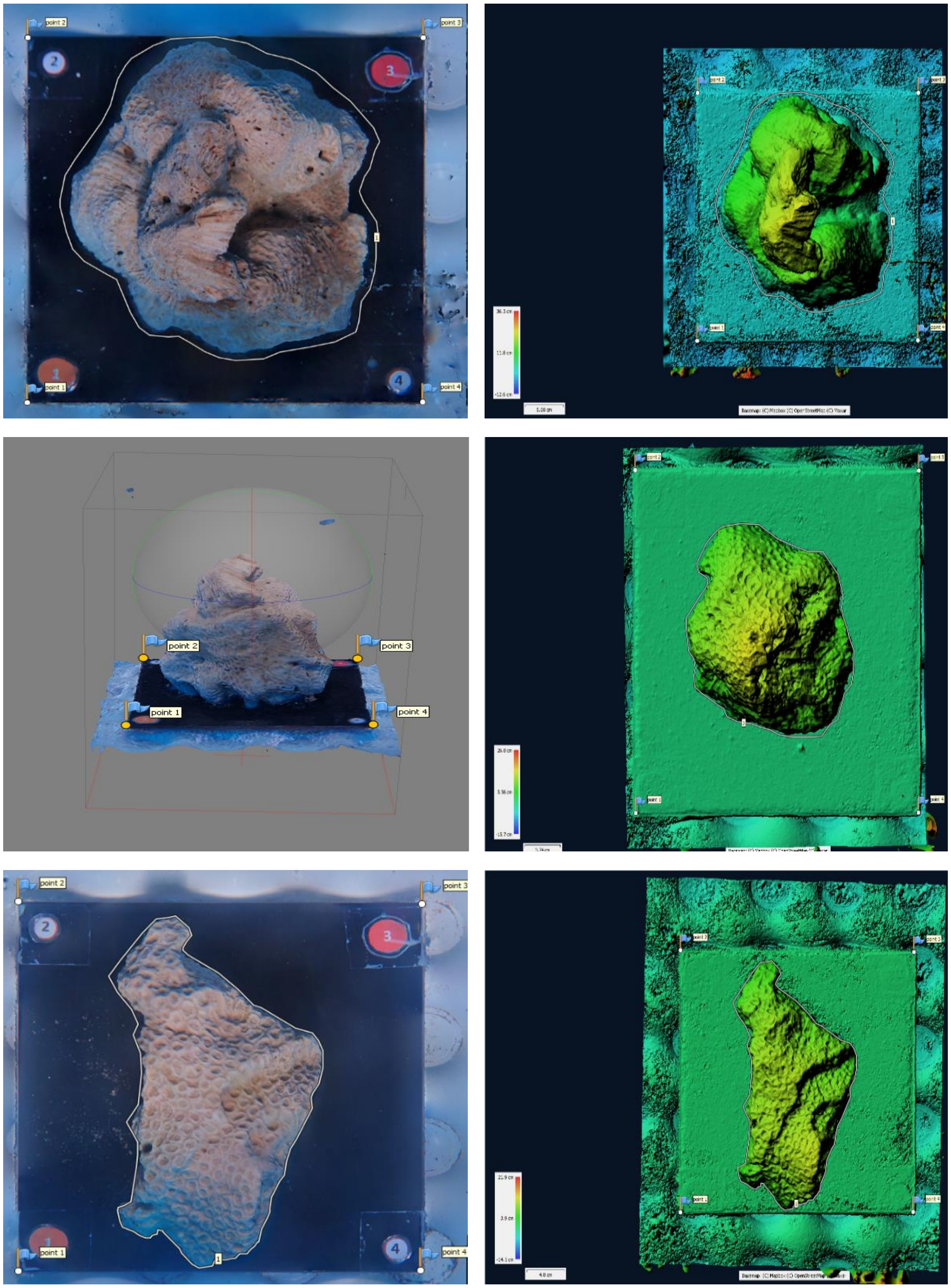

Figure 2. Results from the analysis, using Agisoft Metashape Professional (AMP) software of the digital elevation model (DEM) and three-dimensional photographs of massive (dead) corals.

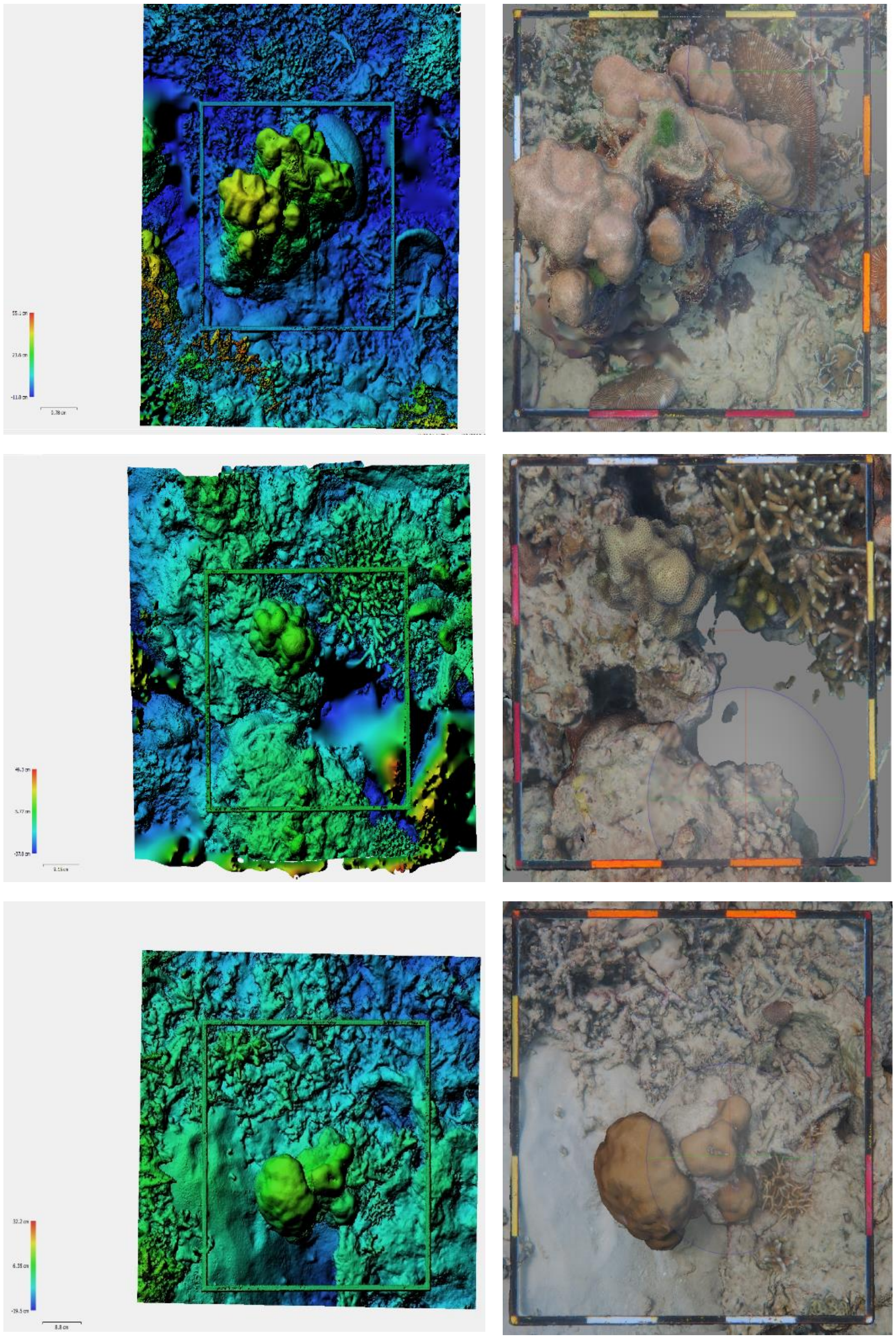

Figure 3. Results from the analysis of the digital elevation model (DEM) and three-dimensional photographs of corals in Gili Labak Island, Sumenep, Madura.

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