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TECHNICAL PAPER

Drone-Transect: a non-destructive operational protocol for drone-based conservation studies on intertidal coral reefs

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ABSTRACT. With many functions attributed to drone use, different applications have been employed along the coastal environment. Most studies have focused on quantifying live and non-live cover, without measuring or quantifying species at the individual level. Thus, we proposed the Drone-Transect method, which, based on aerial images captured by drones, can identify benthic organisms on a broad spatial scale, determining abundance and spatio-temporal distribution. Using the zoanthid *Palythoa caribaeorum*, the method was compared to Line-Intercept Transect (LIT), aiming to verify data precision. Drone-Transect method presented little variation over consecutive days, while LIT revealed a cover variation of 51%. Taking advantage of the ortomosaic, we performed a LIT simulation with 21 repetitions. In each repetition the initial transect was placed one meter from the previous one. The result was a variation coefficient of 33% among the values obtained. In addition, the Drone-Transect method has advantages: it is non-invasive, since researchers are not located on the reefs; it does not require an *in situ* team which makes this method safer; and is faster, the Drone-Transect method can accomplish in 15 min with a single pilot what would take a team of six people three hours using the LIT method. Drone-Transect method is an excellent tool, both for the study of the population dynamics of a specific species and for monitoring benthic communities. It can be applied to studies focused on ecosystem conservation, through the evaluation of coral reef health, especially in conservation units.

Key words: *Palythoa caribaeorum*, Zoantharia, benthos, remotely piloted aircraft, Software SPRING, QGIS.

Transecta con dron: un protocolo operativo no destructivo para estudios de conservación en zonas intermareales de arrecifes coralinos utilizando drones

RESUMEN. Con las múltiples funciones atribuidas al uso de drones, se han desarrollado diversas aplicaciones en ambientes costeros. La mayoría de los estudios se han centrado en la cuantificación de la cobertura viva y no viva, sin medir ni cuantificar especies a nivel individual. En este contexto, proponemos el método *Drone-Transect*, que, a partir de imágenes aéreas capturadas por drones, permite identificar organismos bentónicos a gran escala espacial, determinando su abundancia y distribución espaciotemporal. Utilizando el zoantario *Palythoa caribaeorum* como organismo modelo, el método fue comparado con el método de Transecto de Intercepción Lineal (Line-Intercept Transect, LIT) con el fin de evaluar la precisión de los datos obtenidos. El método *Drone-Transect* presentó escasa variación entre días consecutivos, mientras que el LIT mostró una variación de cobertura del 51%. Aprovechando el ortomosaico generado, se realizó una simulación de LIT con 21 repeticiones. En cada repetición, el transecto inicial se ubicó a un metro de distancia del anterior. Los resultados mostraron un coeficiente de variación del 33% entre los valores obtenidos. Además, el método *Drone-Transect* presenta varias ventajas: es no invasivo, ya que los investigadores no necesitan ubicarse sobre los arrecifes; no requiere un equipo de trabajo *in situ*, lo que incrementa la seguridad durante el muestreo; y es más rápido, permitiendo que un único piloto complete en 15 min una tarea que requeriría tres horas y un equipo de seis personas utilizando el método LIT. El método *Drone-Transect* constituye una herramienta eficaz tanto para el estudio de la dinámica poblacional de especies como para el monitoreo de comunidades bentónicas. Asimismo, puede aplicarse en estudios orientados a la conservación de ecosistemas mediante la evaluación del estado de salud de los arrecifes coralinos, especialmente dentro de unidades de conservación.

Palabras clave: *Palythoa caribaeorum*, Zoantharia, bentos, aeronave pilotada remotamente, software SPRING, QGIS.

INTRODUCTION

Coastal reefs are complex ecosystems of significant ecological importance and have been facing serious threats, amplified by anthropic action (Hoegh-Guldberg et al. 2019; Downie et al. 2024). The combination of these factors makes ecological and long-term monitoring studies extremely difficult, especially considering the dynamic and structural complexity of the environment (Graham and Nash 2012; Joyce et al. 2023). The pursuit of methodological efficiency should emphasize the time taken for data collection, a question that goes beyond the cost, precision and accuracy required in studies in general. The development of methodologies, which always benefits from the evolution of technology, currently provides important tools that can maximize the efficiency of studies in all aspects. How can we therefore take advantage of the most recent technology to perform studies on the ecology and long-term monitoring of coastal reefs? What is the methodological efficiency of the approaches that use these technologies?

Over the years, several methods have been proposed and implemented in the study of reef communities. One of the most used methodologies is the Line-Intercept Transect (LIT) (Loya 1972, 1978), where a transect line is placed on the reef and cover estimates are calculated as a fraction of the total length of the line that is crossed by a substrate or a type of organism (Silva et al. 2015; Steiner et al. 2015). To facilitate data collection in large areas, line-point transects (LPT) or linear point sampling has been suggested (Ohlhorst et al. 1988; English et al. 1997), where data are only sampled at certain points along the line. This method is commonly used in monitoring programs with volunteer participation. Subsequently, the development of underwater photographic cameras allowed for the use of techniques (photogrammetry or video-quadrats) which involve mapping like transects, however from photographic records it is possible to calculate the presence or abundance of organisms (Bayley and Mogg 2020; Jessin et al. 2023).

Due to the local heterogeneity of reefs, as well as differences between locations, estimating benthic cover has become extremely challenging and different debates have arisen regarding the most adequate method (Segal and Castro 2001; Brown et al. 2004; Lam et al. 2006; Nadon and Stirling 2006; Zapata-Ramírez et al. 2023). Different methodologies often vary in terms of data accuracy and precision, in addition to time efficiency and cost. Furthermore, reef characteristics such as inclination, percentage of cover of the study group and roughness, among others, can influence the results of each method (Leujek and Ormond 2007). Similarly, the methodology used can vary based on the aims of the study. For example, when the aim is the comparison of successive estimates, as in any long-term monitoring program, high precision (ability to detect differences) is more important than high accuracy. Additionally, the need for physical access to reefs by the research team could promote the impact of trampling, which could result in behavioral alterations in communities (Vasconcelos et al. 2014). On the other hand, satellite images are used for mapping and monitoring areas; however, they may present a low spatial and spectral, and other pixel parameter resolution or experience alterations due to turbidity and atmospheric conditions, which vary from cloud presence to sunlight reflection on the sea surface (Kabiri et al. 2018; Conti et al. 2020). In any case, considering the complexity, dynamics and heterogeneity of the environment (Trinh et al. 2022; Joyce et al. 2023), the study of reefs faces challenges such as maintaining the standard of randomness and sample representativeness, in addition to difficult access, tidal regimes and the size of the area.

Methods that use Remotely Piloted Aircrafts (RPA), known commonly as drones, have been proposed and tested in many coastal ecosystems including reefs (Joyce et al. 2018: Sierra-Escrigas et al. 2020; Casella et al. 2022). However, challenges commonly arise when using this tool, mainly related to weather conditions and magnetic interference (Bollard et al. 2022; Wang et al. 2025). Additionally, interference when capturing images due to wave deformation can represent an obstacle, together with the reflection of sunlight (Almar et al. 2022). Despite these challenges, the use of drones in the marine environment has increased recently. In the case of reefs, studies on benthic composition, coral health and reef complexity can be found in the literature (Collin et al. 2018; Bennet et al. 2020), in which the identification of categories reflecting distinct substrates above reefs is widespread. Research that separates the environment into abiotic portions, using categories such as 'Rock' and 'Sand', and biotic composition, separating algae and corals, is common (Joyce et al. 2018; Bennet et al. 2020). It is even possible to differentiate substrates that represent healthy corals and bleached corals, which have been implemented in studies with representatives of the genera *Porites* and *Acropora* (Kabiri et al. 2020). Additionally, many benthic organisms have been registered using ecological units, where part of the environment can be included in the classification process. In this case, 17 distinct categories, including 'Waves' and 'Islands' are used as abiotic categories and several biotic units such as Macroalgae, Seagrass, *Millepora*, *Siderastrea siderea*, *Zoanthus*, *Caulerpa* and *Palythoa* are used. Therefore, not all organisms are analyzed at the species level (Sierra-Escrigas et al. 2020). Many studies explore mapping communities and the environment; however, few carry out specific measurements of organisms, only considering the area that the species covers (Zapata-Ramírez et al. 2023). Although the use of RPAs has many applications, refinement is still necessary, both for smaller-scale organisms and for accompanying the cover and specific distribution of key organisms. This species-specific approach allows for the understanding of the spatio-temporal dynamic of the reef community and can provide information that is fundamental for the adequate management and conservation of reefs.

We propose the Drone-Transect methodology, which can identify and quantify benthic reef organisms in intertidal zones. We tested the precision of this method through comparisons with the Line-Intercept Transect method (Loya 1972, 1978). The study was developed in the coastal region of North-eastern Brazil, characterized by the presence of tropic fringe reefs (Leão et al. 2016), comprised of a diverse community of mainly algae and zoanthids (Aued el al. 2018), and where the most abundant species is *Palythoa caribaeorum* (Duchassaing and Michelotti, 1860). This zoanthid is typically found in shallow waters in tropical and subtropical regions of the Western Atlantic (Reimer et al. 2007; Silva et al. 2015), where it occupies large areas in intertidal zones, forming extensive and easily identified mats (Reimer et al. 2006; Barradas et al. 2010) and presents high variation in abundance throughout the year (Costa et al. 2011). The zoanthid *P. caribaeorum* is an ideal species for evaluating the Drone-Transect method because: 1) it is easily identified by its distinctive morphological characteristics; commonly known as ‘ox slaver’ it secretes a characteristic mucus which covers colonies to prevent desiccation during low tide exposure (Soares et al. 2006), giving it a characteristic texture and colouration; 2) it is easily observed with the naked eye, allowing reliable identification in aerial images; and 3) it is one of the dominant benthic organisms on exposed reef flats during low tide, often exhibiting extensive spatial cover. Furthermore, due to its high abundance, this species plays an important role in reef competitive dynamics, including competition with scleractinian corals (Bastidas and Bone 1996). Thus, we used the zoanthid *P. caribaeorum* as a model to verify if the Drone-Transect method can identify, delineate and quantify colonies of *P. caribaeorum* more precisely than the Line-Intercept Transect method (LIT). Specifically, we tested the hypotheses that the Drone-Transect: a) is more precise compared to the Line-Intercept Transect; b) represents a faster, more economically and less environmentally impactful method than LIT; and c) presents significantly different results from LIT.

MATERIALS AND METHODS

Study area and target species

The protocol was tested on Serrambi beach, located in the municipality of Ipojuca, in the state of Pernambuco, Brazil (8° 33′ 21″ S and 35° 00′ 21″ W) (Figure 1). Beach rocks, i.e. sandstone fringe reefs which extend parallel to the beach, can be found in the area covering approximately 2 km by 0.7 km at the widest portion, part of which is emersed during low tide and completely submerged during high tide (Jales et al. 2012). The study was performed on the reef located at Pontal de Serrambi, which was easily accessible for data collection (Figure 1). The area is characterised as hot and humid, with an average annual temperature of 24.7 °C, with average annual rainfall of 1,239 mm. The area presents two distinct periods in terms of rainfall: a dry season which lasts from September to February (spring-summer), and a rainy season from March to August (autumn-winter) (Me-

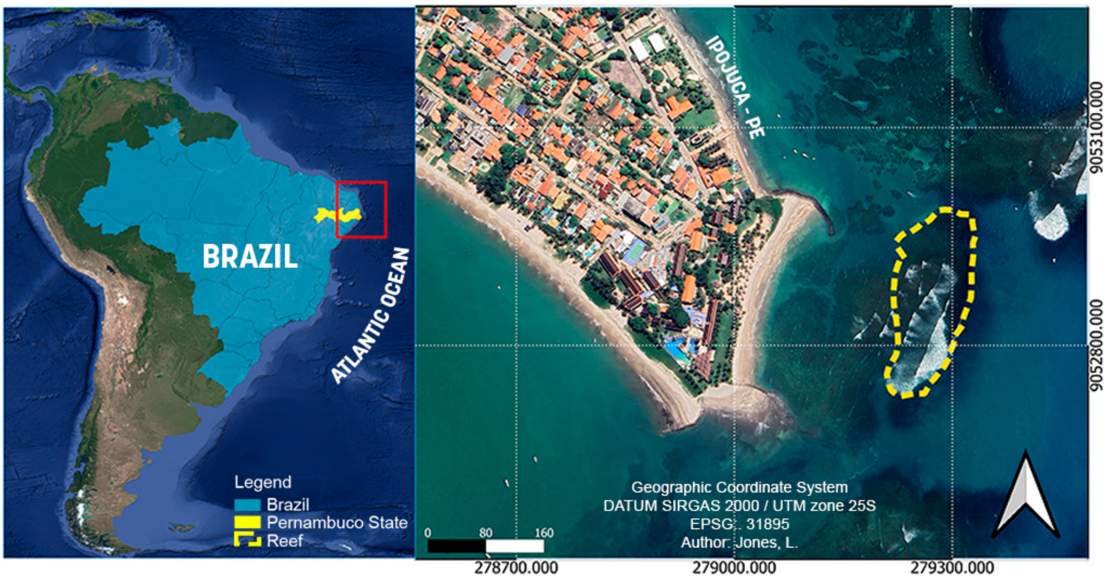

Figure 1. Location of the study area. The state of Pernambuco (yellow) and the reef (dotted line). Modified from satellite images from Google Earth using QuickMapService plugin

deiros et al. 1999). The species used as a model for this study was the zoanthid *Palythoa caribaeorum*, which is distributed across the tropical western Atlantic from Florida to southern Brazil, including oceanic islands and Cape Verde (Reimer et al. 2007, 2010; Silva et al. 2015). It is highlighted as a dominant species due to its elevated growth rate and competitive abilities (Bastidas and Bone 1996; Silva et al. 2015), forming extensive mats with significant variations in cover along the Brazilian coast and throughout the year (Costa et al. 2011; Aued et al. 2018).

Drone-Transect Method

Data collection

Data were collected using a RPA (DJI Phantom 4 Pro), equipped with a 20-megapixel 1-inch CMOS sensor and an 84° field-of-view (FOV) lens (8.8 mm/24 mm equivalent, f/2.8-f/11) with autofocus at 1 m-∞. The aim of the flight was to define the area of cover, and parameters such as flight height and mission route were tracked using the software 'Maps made Easy', where the degree of frontal and lateral overlap was set at 80% (Figure 2 A). The flight took place at a height of 60 m above ground level, with a duration of approximately 15 min (approximately 160 images were taken per flight) and the spatial resolution of the photographs was 3 cm. The whole area was recorded. The ground clearance of 60 m was defined, following preliminary tests involving different heights, as it allowed for good identification of zoanthid colonies during a continuous mission time within the battery's autonomy limits. The same routes and heights were used in all campaigns.

Image processing

Images were processed using Agisoft Metashape (AgiSoft 2024) to obtain orthomosaics, and photographs were grouped together in a single archive containing the entire study area (Figure 3).

Images were segmented and classified using SPRING software (Câmara et al. 1996) provided by the National Institute of Spatial Research (INPE). The mosaic was classified by region, and

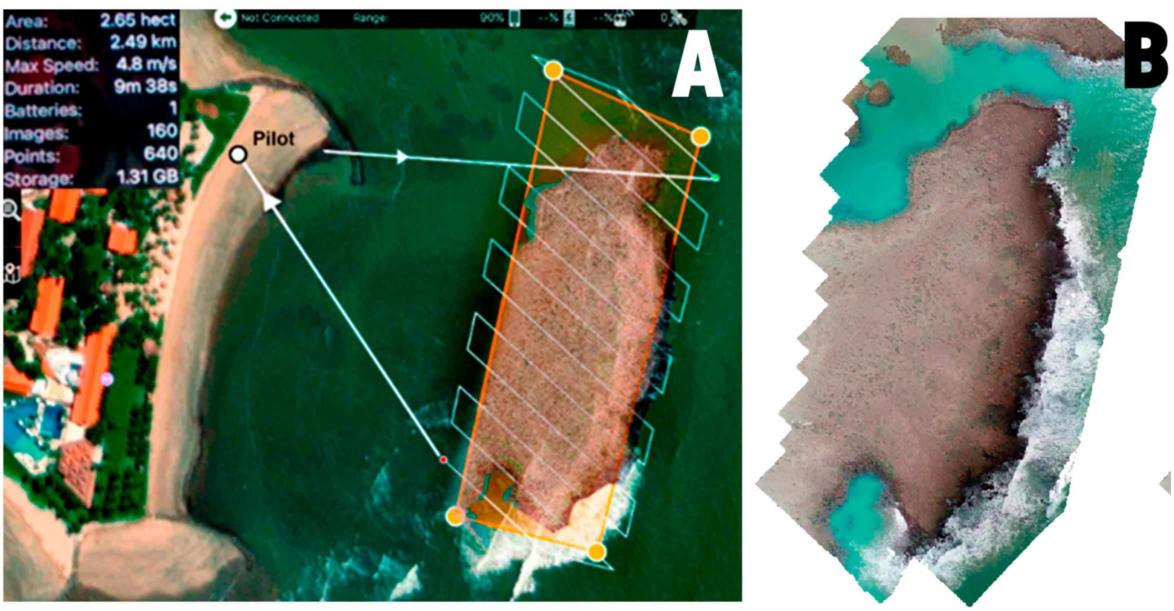

Figure 2. A) Representation of the drone flight route over reef in Serrambi beach, PE, with details of the flight parameters. B) Illustrative image that represents the RGB orthomosaic, base structure generated from aerial photographs.

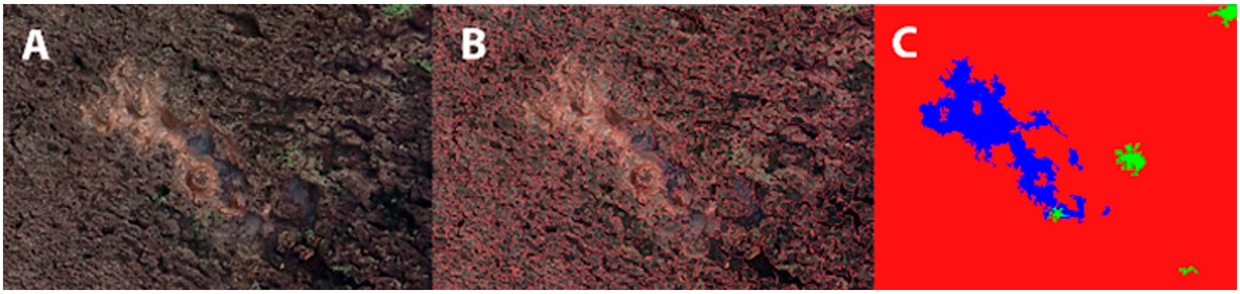

Figure 3. Stages of processing: orthomosaic highlighting *Palythoa caribaeorum* (A), representation of segmentation (B), area classification: Substrate in red, *P. caribaeorum* in blue, Algae in green (C).

the archive was segmented considering area and similarity (Gonzalez and Wintz 1987). At this point, numerical values that would segment regions and similar zones were defined (Figure 3 B). These parameters were obtained through trial and error (Cândido et al. 2015) until the ideal values were reached, allowing a good delimitation of the area of interest. Tests were conducted using decreasing parameter values, starting with an area threshold of 1,000 and a similarity threshold of 100. Values were reduced by 50 for the area parameter and by 10 for the similarity parameter at each iteration. Values of 100 for area and 10 for similarity were considered ideal for the annotations, considering both annotation quality and processing time. When segmentation was identified, pixel information was extracted for subsequent training of the system to classify reef cover, where the area was classified by substrate, *P. caribaeorum*, and algae (Figure 3). The definition of the class 'algae' was used to differentiate regions of low pigmentation that conflicted with '*Palythoa caribaeorum*'. A training stage was carried out to classify areas, where the selection tool in SPRING was used to indicate the region corresponding to the class of interest. The training resulted in a set of markers for each class, which were used as a reference for classification by the software. Each click on a determined region generates a selection that encompasses similar areas. If the marker was correct, it was assigned to the class. Classes were considered categorical groups that separate regions. In this case, we separated three classes: 1) substrate (red); 2) *P. caribaeorum* (blue); and 3) algae (green) (Figure 3 C). Each class was treated individually, grouping similar regions. The classification algorithm used was Battacharya with an acceptance threshold of 99.9 %, ideal for estimating density and delimiting regions. This algorithm measures the statistical distribution that separates classes defined by the training (Câmara et al. 1996; Ruddorf et al. 2005). For the quantification of the total area, a vector polygon was drawn, delimiting the entire extension of the reef.

The classification generated in the SPRING software was exported in vector format (Shapefile) and imported into QGIS (QGIS 2023). A visual inspection was then performed for potential spectral confusion that might have occurred during the classification process, and corrections were made when necessary. The area was subsequently calculated in m^2. This process was used to ensure that the area of *P. caribaeorum* colonies was as accurate as possible. With these values in hand, it was possible to calculate the cover of *P. caribaeorum* using the Drone-Transect method. The value obtained from the polygon encompassing the entire reef was used to quantify cover. The cover, estimated by the Drone-Transect in square meters and percentage, was compared with records obtained using the LIT method.

Line-Intercept Transect (LIT)

This method required a six-people team to cover the entire area during low tide. The group was divided into three pairs, each carrying a 50 m measuring tape distributed in the northern, central and southern sectors of the reef. Each pair conducted three transects in each sector, perpendicular to the beach line totaling 9 for the entire reef (southern sector T1-T3; central sector T4-T6, and northern sector T7-T9) (Figure 4 A). Each transect started at the tideline, on the side of the reef facing the beach and continued until the tideline of the opposite side. The first transect was positioned randomly at the extreme south of the reef and from there, each transect was separated from the next by 30 m (Figure 5 A). The presence of *P. caribaeorum* was recorded (in cm^3) in a spreadsheet along the transect line (Figure 4 B-D). Values obtained were used to calculate the cover of colonies on the reef (in %).

Sampling design

With the aim of observing variations in the short and long term, three data collection campaigns were carried out, all of which were undertaken during the morning and at low tide when the reefs were exposed and there was good luminosity. The

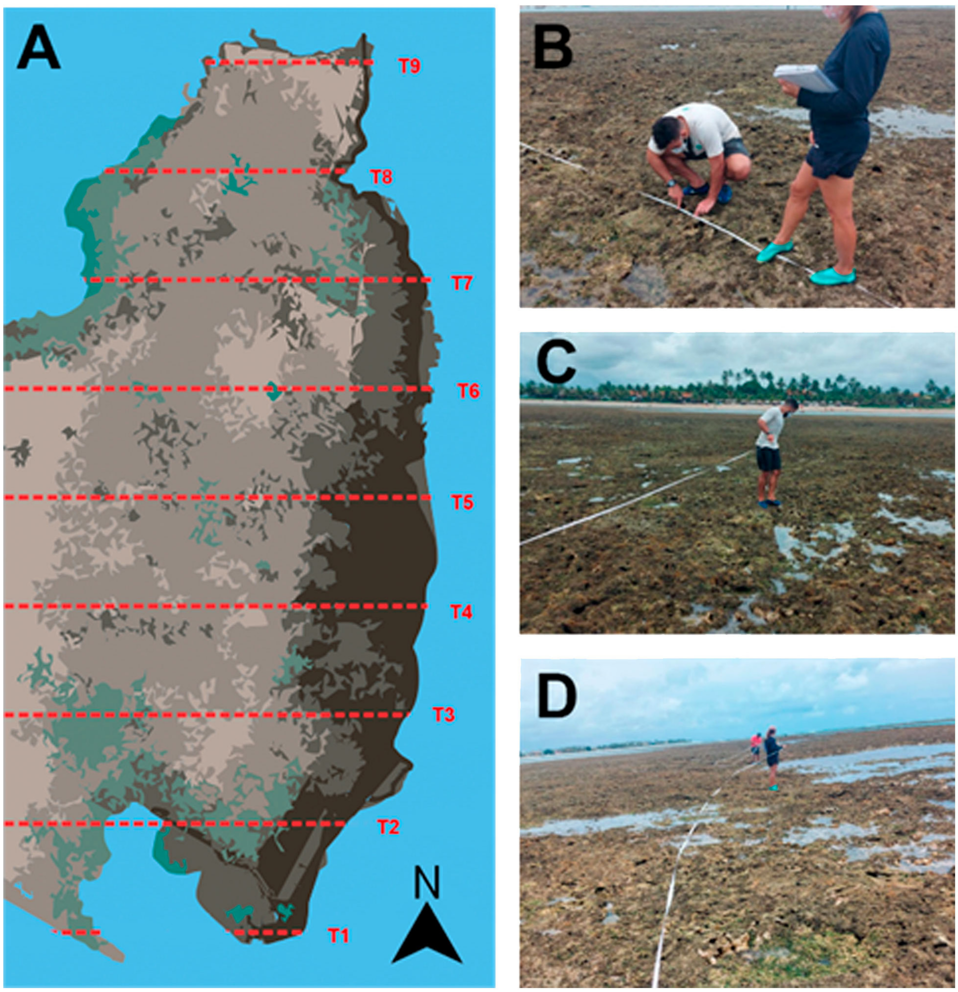

Figure 4. A) The reef of Serrambi beach, with representations of transects used in the LIT method (T1-T9). B) Measuring process (LIT) of a research pair. C) Positioning of transects. D) Extension of transects. Photo by Carlos D. Pérez.

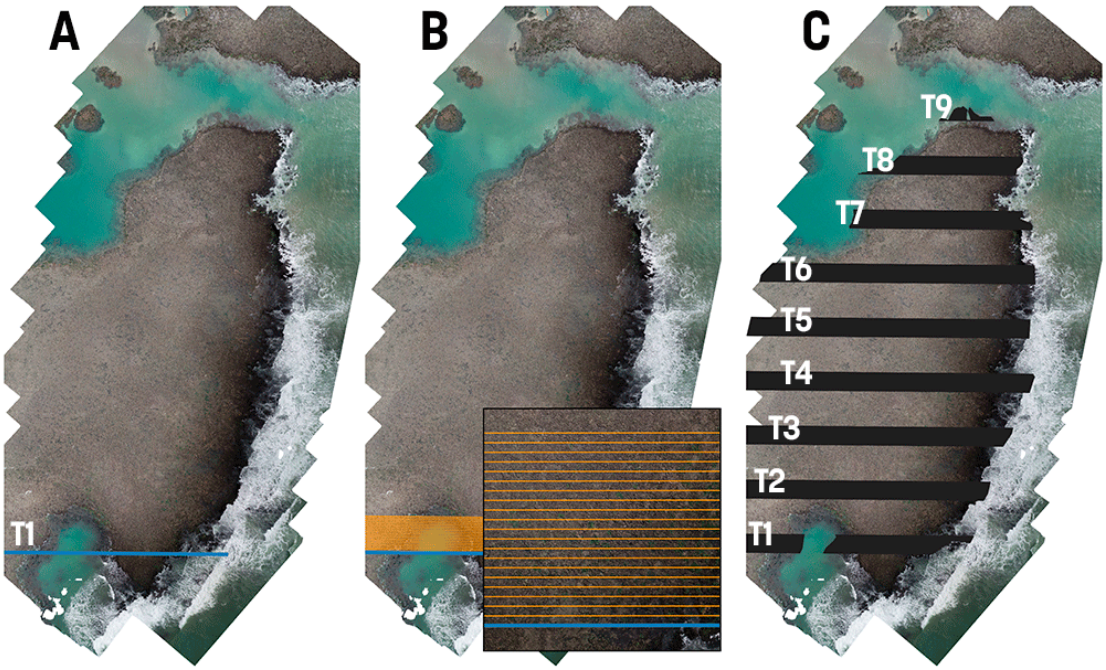

Figure 5. A) Representation of the Transect location (T1). B) Representation of the 21 repetitions of T1. C) Final representation of the 21 simulated repetitions.

first was carried out during the dry period (26 February 2021) and two during the rainy period (23-24 July 2021). During each campaign, both the Line-Intercept Transect (LIT) and Drone-Transect methods were used. Data collection during distinct periods and over consecutive days was important for evaluating the precision of each method tested. Considering the minimum alterations in colony size over a one-day interval, we determined cover to be similar over a 24-h period. Discrepant records between consecutive days were considered a lack of precision. To evaluate the method's effectiveness in analyzing temporal variations in cover, the variation in data obtained with the two methods was compared between samples 1 and 3, approximately 6 months apart (Table 1).

Simulation of the Line-Intercept Transect Method

In addition to collecting data using the Line-Intercept Transect and Drone-Transect methods, a LIT simulation was performed using digital spatial analysis tools (Figure 5). Since the Drone-Transect method permitted the creation of a virtual reef (orthomosaic) with distributed *P. caribaeorum* colonies, it was possible to perform simulations of LIT samples (T1-T9). The LIT simulations were positioned to assess how the randomness of the transect placement could influence the precision of results using the traditional methodology.

The simulation consisted, a priori, of an initial transect (Figure 5 A), drawn from east to west, crossing the entire orthomosaic. Using the Parallel Array function available in the QGIS software, this linear transect was repeated virtually 20 times, parallel to the north with 1m between repetitions, resulting in 21 repetitions in the first transect (T1) (Figure 5 B). The features of the layer encompassing the transects were separated into independent layers. Starting from each repetition of T1, now independent in isolated layers, a set of nine transects was generated using a new Parallel Array, this time separated by 30 m. The process was repeated

Table 1. Mean cover of *Palythoa caribaeorum* on Serrambi reef estimated using the Drone-Transect and Line-Intercept Transect (LIT) methods on three sampling dates, as well as the mean cover derived from LIT simulations (n = 21).

Dates	DT			LIT			LIT Sim.		
	Total area (m^2)	Cover area (m^2)	%	Total area (m^2)	Cover area (m^2)	%	Total area (m^2)	Cover area (m^2)	%
26 February 2021	33.193.516	336.607	1.01	10.225	0.1159	1.13	-	-	-
23 July 2021	33.193.516	179.543	0.54	8.952	0.1587	1.77	10.721	0.0789	0.73
24 July 2021	33.193.516	162.765	0.49	9.867	0.2396	2.49	-	-	-

for each layer, resulting in 21 repetitions of the procedure which simulated *in situ* LIT sampling, where each set of 9 transects was repeated at 1 m from the previous set (Figure 5 C). Lastly, each layer received a 0.05 cm buffer so that each transect repetition would have a thickness of 1cm, simulating the tape measure used in the LIT method and therefore, able to calculate the covered area of *P. caribaeorum* in m^2. Thus, in each repetition, the cover of the zoanthid was calculated in the orthomosaic image, based on the outlined transects (T1-T9), following the same methodology as LIT. To test the hypothesis that transect placement in the LIT method influenced the precision of the method, the coefficient of variation was calculated for the cover of *P. caribaeorum* obtained in the 21 repetitions in each transect (T1-T9).

Data analysis and method comparison

The analyses were performed based on the percentage cover of *P. caribaeorum*, calculating the percentage of different shapes based on the methods used. For the Line-Intercept transect method, the percentage of cover was calculated for each sample date. As such, the area occupied by *P. caribaeorum* was summed across the 9 transects analyzed each day and divided by the sum of the total area of the transects. Therefore, a single percentage cover value was obtained for each day analyzed. For the Drone-Transect method, the polygons corresponding to the areas occupied by *P. caribaeorum* were summed using the field calculator and the 'statistics' tool available in the QGIS software. The calculation was performed for each collection date, and the result of each day was divided by the total reef area obtained from the polygon. As with the LIT method, a single percentage cover value was obtained for each analyzed day. Finally, for the simulation, the cover analysis was carried out in a similar manner to that of the *in situ* LIT, i.e. the percentage cover was calculated for each of the 21 replicates. Unlike the other two approaches, it was feasible to quantify the percentage of cover for each replicate, allowing the mean and variance coefficient derived from the dataset to be calculated. The simulation was performed with the data obtained on 23 July 2021.

Two types of comparisons were made, one involving two consecutive days (covering the LIT and Drone-Transect methods) and the other involving the Drone-Transect method with the simulation, although in this case, both in a single day. The first comparison aimed to verify the reliability of each method across days. Assuming that zoanthid cover does not vary significantly from one day to the next, the effectiveness of the methods can be assessed by measuring the variation in the data obtained between the two consecutive days. The second comparison, using the simulation results from a single day (23 July 2021), aimed to test the hypothesis that the result of the mean cover of the

21 simulations was significantly different from the cover measured by the Drone-Transect method. As the data set consisted of a single percentage value for the Drone-Transect method, this value was used individually in the one-sample *t*-test, serving as a basis for comparisons with the sample consisting of the set of 21 percentages obtained in the simulation. In other words, a one-sample *t*-test was used to compare the simulation's mean percentage against a single value obtained by the Drone-Transect method. This allowed an indirect comparison between the LIT and Drone-Transect methods using the simulation as a reference and observing whether the average obtained by the simulation differed from the value calculated from the Drone-Transect method.

Method feasibility

To evaluate the cost-benefit of the Drone-Transect method relative to LIT, qualitative factors influencing the performance and applicability of both methods were assessed. The following factors were considered: the number of field personnel involved, travel costs, food resources, application time, the risk of accidents and trampling in the area.

RESULTS

Drone-Transect process and LIT sampling

The Drone-Transect method generated three orthomosaics (Figure 6), one for each sample date. Initially, during the first survey conducted on 26 February 2021, the percentage cover estimated by the LIT and Drone-Transect methods was similar. Considering data obtained during consecutive days in July (Table 1), the Drone-Transect method presented a slight variation of approximately 9% in the values of *Palythoa caribaeorum* cover between days, while LIT presented a variation of 51%, demonstrating the lower precision of this method compared to the Drone-Transect method.

LIT Simulation

Simulations generated 21 sample packages from nine transects each (T1-T9; Table 2). It was possible to infer that the LIT method was not very precise, since a comparison of the 21 simulations yielded a coefficient of variation of 33%, with a percentage of cover that varied from 0.40 to 1.20%. This result revealed a high variation between repetitions, which could lead to overestimation or underestimation of the real cover of *P. caribaeorum* on the reef. This means that in a traditional field study, a simple 1-m shift from the initial transect installation point can generate significant variation in the final results. The randomness of the transect placement in the field could lead to very different results, which could directly affect subsequent analyses (Table 2). The comparison of average percentage of cover for 07/23 obtained by the LIT simulation and the Drone-Transect confirmed our hypothesis, presenting significant differences ($t = 3.6188$, $DF = 20$, p-value = 0.0017, $\alpha = 0.05$).

Method feasibility

Initially, the Drone-Transect approach reduced the number of researchers circulating over the reef environment because only one person capable of operating the drone was required (Figure 7). Consequently, the costs related to travel and accommodation were reduced, with only one small vehicle required, resulting in reduced fuel consumption. The biggest expense for the Drone-Transect method was the purchase of a drone, which is recommended due to the cost of contracting a mapping service, where daily rates were 10% of the total cost of a drone. The greatest advantage of the Drone-Transect method was the time taken for data samples (images). Where six researchers take approximately 3 h to position and quantify the transects, an aerial mission can cover the same area in approximately 15 min. For intertidal environments, this factor was of vital importance due to the rising tide level during data collection. Furthermore, the

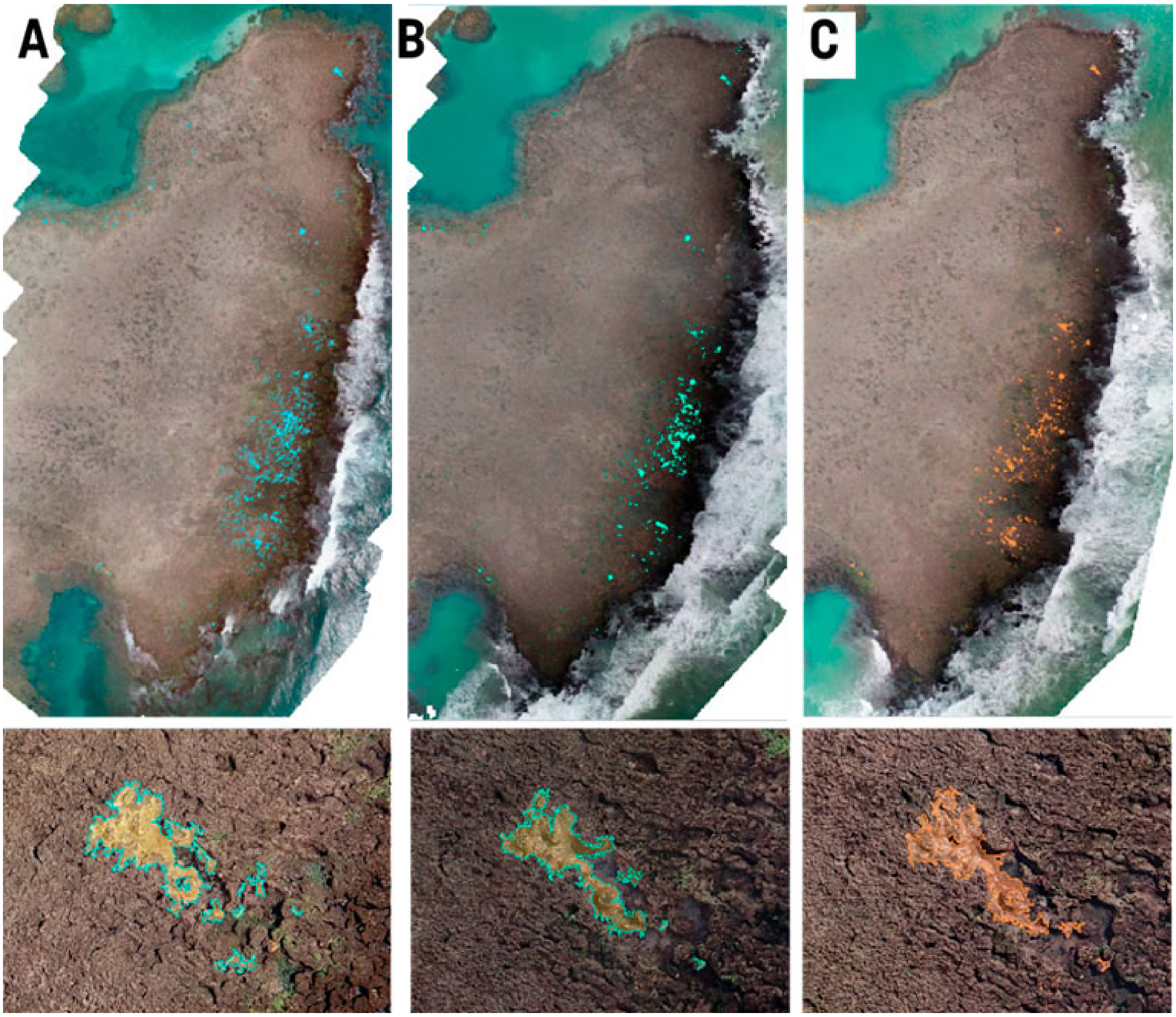

Figure 6. Orthomosaics referring to the analyzed reefs, highlighting the Palythoa caribaeorum colonies separated by colors that correspond to the days. A) 26 February 2021. B) 23 July 2021. C) 24 July 2021.

reef's rugged topography can become a risk factor, leading to accidents. The Drone-Transect method, which is considered non-invasive, preserved the researcher's physical integrity by keeping them fixed at their initial position outside the reef, on the beach's sand line. Furthermore, the six-person team's work on top of the reef resulted in a high level of trampling in the region, which directly impacted the benthic community and becomes a harmful practice in sensitive areas or conservation units.

DISCUSSION

Based on the results obtained when using the zoanthid *P. caribaeourm* as a biological model to compare Drone-Transect and LIT methods, the former was more efficient in identifying, delimiting and quantifying the studied colonies. The two approaches produced distinct results, and in addition to being faster, more economical and less envi-

Table 2. Line-Intercept Transect (LIT) simulation on the virtual Serrambi reef on 23 July 2021. Each repetition represents a set of nine transects positioned 1-m apart from the previous set. Minimum and maximum cover of *Palythoa caribaeorum* obtained in bold. SD = standard deviation; CV = coefficient of variation.

Simulation repetition	Repetition (m^2)	Cover area (m^2)	Cover area (%)
Repetition 1	10.995	0.0811	0.737
Repetition 2	10.37	0.0476	0.459
Repetition 3	10.895	**0.0439**	**0.403**
Repetition 4	10.886	0.0581	0.533
Repetition 5	10.888	0.0679	0.624
Repetition 6	10.822	0.0897	0.828
Repetition 7	10.809	0.0763	0.706
Repetition 8	10.774	0.0653	0.606
Repetition 9	10.735	0.094	0.876
Repetition 10	10.708	0.0652	0.609
Repetition 11	10.698	0.0616	0.576
Repetition 12	10.682	0.0517	0.484
Repetition 13	10.665	0.0519	0.487
Repetition 14	10.667	0.086	0.806
Repetition 15	10.676	0.0835	0.782
Repetition 16	10.673	0.127	1.19
Repetition 17	10.666	0.0592	0.555
Repetition 18	10.655	0.078	0.732
Repetition 19	10.64	0.1182	1.111
Repetition 20	10.631	0.1229	1.156
Repetition 21	10.646	**0.1273**	**1.199**
Mean		0.0789	0.736
DP		0.0263	-
CV		33.37%	-

ronmentally impactful, the Drone-Transect method was more precise than the LIT method. When observing consecutive days, the Drone-Transect method shows minimal variation in cover, while LIT presented high variation. This variation cannot not be explained by the natural growth of the zoanthid, since its growth rate is slow and does not present daily variation (0.0015 to 0.021 cm^2 day^{-1}, Silva et al. 2015; 0.004 cm^2 day^{-1}, Bastidas and Bone 1996; 0.36 cm^2 day^{-1}, Rabelo et al. 2013). On the other hand, the analysis of the Drone-Transect method presented some variation, although much lower than that observed when using the LIT method. The Drone-Transect method varied by 9% between two consecutive days, which can be explained by the topographic complexity and biogenic composition of the environment (Casella et al. 2020), the collection time, lighting and some losses caused by solar interference (glitches) (Mount 2005; Kabiri et al. 2018; Joyce et al. 2018). One point worth highlighting is that the Drone-Transect method scans the entire reef (33,193.516 m^2),

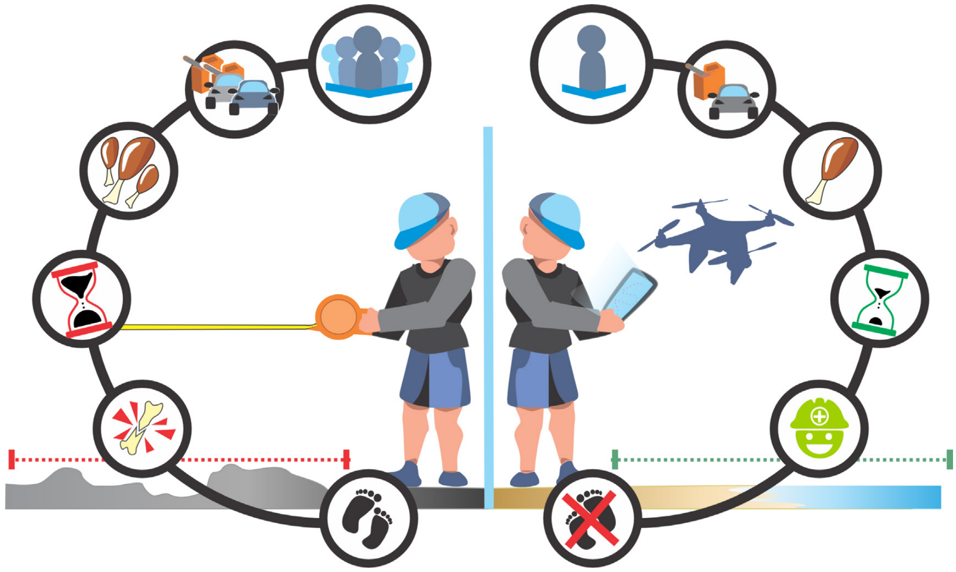

Figure 7. Infographic referring to the characteristics of the compared methods, relating the pros and cons of each method: Drone-Transect (right) versus Line-Intercept Transect -LIT (left).

while the 51% variation in the LIT method was in a sampled area of approximately 9 m^2. In fact, the Drone-Transect method is a census of the total area in question, while LIT is a sampling method (only 0.027%) of the total reef area, which results in a greater representativeness of the data obtained by the former. The LIT simulation was found to be extremely variable, since it depends on the randomness of transect positioning on the reef, observing a coefficient of variation of approximately 33%. This leads in a lack of precision in traditional sampling, since a 1-m displacement in the initial transect can under- or overestimate the cover of the organism in question. In isolated records, the sample cover can be twice as high compared to other replicates.

Studies aimed at monitoring coastal environments using aerial images are committed to verifying the abiotic and organic cover of components based on classes that separate substrates. Cornet and Joyce (2021), for example, sought to characterize coastal regions spectrally by attaching a spectroscope to a drone. This allowed them to differentiate and quantify the cover of the classes 'Rock', 'Sand', 'Coral' and 'Algae'. In addition to quantifying cover, the study grouped corals into a single class, making it impossible to survey groups of interest. Sierra-Escrigas et al. (2020), identified 17 classes based on aerial scanning, highlighting benthic representatives grouped into ecological units. Thus, organisms were classified into classes, such as '*Zoanthus-Caulerpa*', '*Millepora-Palythoa*', 'Coral-Algae'. From this perspective, portions of the environment can be attributed to ecological units, considering physical and geological characteristics, as well as some of the dominant organisms (Díaz et al. 2000; Sierra-Escrigas et al. 2020). Hamad et al. (2022) employed aerial images associated with underwater photographs, where it was possible to identify Sediments, Macroalgae, Corals and Marine Phanerogams (Seagrass) using the drone, of which the latter was the focus of the study. Once again, several organisms were grouped in this same category, therefore, the union of capturing underwater images allowed for the identification of six distinct species, making the combination of techniques an extremely rich practice.

By inserting one or more components per class, there is a significant loss in the individual analysis of target species. On the other hand, the Drone-Transect method proposed in this study goes beyond class-based approaches, since the researcher trains the system to identify them based on predefined parameters for each collection. Implementing this new method opens a wealth of possibilities with ecological studies at a spatio-temporal scale, allowing for the evaluation of parameters that are difficult to analyze with current methods, such as the growth rate and mortality of colonial organisms in an entire population. Consequently, the Drone-Transect method allows for the long-term monitoring of a population and subsequent overlay of orthomosaics to estimate lost and new areas within a given population. In terms of cost-benefit, the Drone-Transect method stands out for its cost effectiveness related to field crew deployment, including fuel and food costs. Thus, a major advantage of this method is the time required to scan the area at a high speed and the preservation of benthic communities in the area. With the use of the Drone-Transect method, benthic communities do not suffer from trampling, as is commonly observed with the LIT method. This can cause varying degrees of damage to communities, from loss of biomass and density to imbalances in the food web (Kay and Liddle 1989; Sarmento and Santos 2012; Avelino et al. 2023). It is estimated that excessive trampling is a potential agent of deleterious changes in a reef community, affecting several sensitive organisms and resulting in the loss of richness (Woodland and Hopper 1977; Máximo et al. 2019). On the other hand, processing time could be seen as a negative aspect of this method. Visual inspections are considered safer for organism identification, but they involve a low area of cover and high financial costs (Kabiri et al. 2020). In this study, training was only used for one class representing an easily identifiable species, therefore, further studies are required for the inclusion of new organisms in the area classification. However, using a more powerful computer or assigning processing to a virtual environment (cloud) can speed up processing. The Drone-Transect method uses a commercial drone, including the built-in sensors and cameras. There is no inclusion of annexes such as spectrometers (Cornet and Joyce 2021) and most of the software used was free, except for Agisoft Metashape. These factors, which characterize the method as low cost, confirm, in qualitative terms, the hypothesis that this method offers a more advantageous alternative from a cost-benefit point of view.

The Drone-Transect protocol should be regarded primarily as an ecological monitoring tool rather than a method intended for comprehensive reef fauna surveys. Its main purpose is to track reef dynamics over time through repeated assessments of the cover and spatial distribution of dominant benthic organisms that can be readily distinguished in aerial imagery, thereby enabling standardized, non-destructive, and low-effort quantification of temporal changes over large spatial scales. Although this study used the zoanthid *P. caribaeorum* as a model species, the protocol can be equally applied to other conspicuous and dominant reef organisms, such as sea urchins, barnacle aggregations, mussel and macroalgal beds, and coral species with distinctive colony morphologies that are readily identifiable in high-resolution imagery. Consequently, the protocol is particularly well suited for monitoring changes in the abundance, distribution, and dominance of key benthic taxa over time. Conversely, it is not intended to replace traditional ecological surveys designed for biodiversity inventories or the identification of rare, cryptic, or morphologically similar species, for which direct field observations remain indispensable. Rather than competing with conventional survey methods, the Drone-Transect protocol should be viewed as a complementary approach that expands the spatial and temporal scope of reef monitoring while minimizing field effort and disturbance to the ecosystem. In addition to monitoring reef community dynamics and benthic dominance patterns, the protocol has considerable potential for assessing reef health, particularly through the detection and quantification of bleaching events in zoanthids and corals, thereby broadening its applicability in long-term ecological monitoring and conservation programs.

In summary, considering the current context of reef degradation and above all, the prospect of future environmental crises, it is necessary to increasingly employ more technologies that enable the use of methodologies with faster, more accurate and precise solutions, in addition to non-invasive methodologies that facilitate access (including from a cost-effective perspective) and good reproducibility. Good reproducibility of this set of characteristics is important when considering the dynamic of ecological processes in reef environments and the need for short, medium and long-term monitoring. After all, coastal reefs combine high complexity, extreme ecological importance and strong anthropic threats, all of which are occurring faster and becoming more evident. Thus, it seems illogical, in the era of technological revolution, to maintain invasive methods that depend on the randomness of sampling, as in such heterogeneous environments data samples become very imprecise. Our results reinforce the need to invest in non-invasive technologies for field data surveys, which, in addition to being more accurate and precise, offer a broad range of analyses. The Drone-Transect method is an excellent tool both for studying the population dynamics of a particular species and for monitoring intertidal benthic communities, aiming at ecosystem conservation through the analysis of coral reef health, especially in conservation units (CU).

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Lynick Jones: conceptualization, methodology, investigation, writing-original draft. Anny K. A. A. C. Bolognez: investigation, writing-review and editing, validation. Normades Matos da Silva: investigation, writing-review and editing, validation. Thiago H. de Melo Silva: investigation, writing-review and editing. André M. Melo Santos: investigation, statistical analyses, writing-review and editing. Paula Braga Gomes: writing-review and editing, validation. Carlos D. Pérez: supervision, conceptualization, investigation, writing-review and editing validation.

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