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Comparison of Standard Caribbean Coral Reef Monitoring Protocols and Underwater Digital Photogrammetry to Characterize Hard Coral Species Composition, Abundance and Cover

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The precise assessing and monitoring of coral reefs are necessary to address and understand the threats and changes in coral communities. With the development of new technologies and algorithms for image processing, new protocols like underwater photogrammetry are implemented to study these ecosystems. This study compares the main ecological metrics for reef condition assessment, obtained with an underwater digital photogrammetry protocol (UWP) and traditional sampling design simulations in coral reefs of the Cozumel Reefs National Park. Three orthomosaics (380 m^2) per reef on six fringing reefs were constructed, and the hard coral community characterized using a Geographic Information System (GIS). The orthomosaics were also used as a basis to simulate transect lines and obtain data on the hard coral community according to the video transect (VT) protocol, point intercept (PIT) protocol, and the Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocol. Higher colony abundance, species richness, and lower coral cover estimates ($p < 0.05$) were obtained with the UWP. This protocol was also sensitive to small sized species. All the sampling designs showed similar capability to identify dominant species in terms of colony abundance and coral cover. The VT, PIT, and AGGRA showed similar coral cover values ($p > 0.05$), which seems to indicate that these sampling designs overestimate this important metric. Our results will help to understand and integrate the observations obtained with UWP with long-term data obtained with commonly used monitoring protocols in the Caribbean region.

Keywords: underwater photogrammetry, coral reef monitoring, standard monitoring protocols, ecological metrics, coral cover

1. INTRODUCTION

The depletion of coral reefs and the rapid loss of living coral tissue are a consequence of a synergy of disturbances of human and natural origin, and effects related to climate change (Jackson et al., 2001; Hughes et al., 2003, 2018; Pandolfi et al., 2003; Steffen et al., 2011). Since the early 1990s, several systematic visual surveys have been used throughout the Caribbean and other regions, for the evaluation and monitoring of coral reef ecosystems (English S, 1997; Hill and Wilkinson, 2004). Widely used protocols in the Caribbean include the line intercept transect protocol (LIT), point intercept transect (PIT) protocol, Caribbean coastal marine productivity (CARICOMP) protocol, and Atlantic and Gulf Reef Rapid Reef Assessment (AGRRA) protocol (http://www.agrra.org/), Reef Check (http://www.reefcheck.org), among others (for details see English S, 1997; Kjerfve, 1998; Hill and Wilkinson, 2004; Lang et al., 2010; Jokiel et al., 2015). These protocols are based on the counting of points having as sampling unit line-transects, which were previously established by Loya (1972) and Porter (1972). Quadrants and images obtained by means of underwater photography or video were later incorporated, and are also commonly used to estimate relative percentages of cover of reef benthic organisms and other key ecological attributes such as species richness and colony abundance (Aronson et al., 1994; English S, 1997; Kjerfve, 1998; Hill and Wilkinson, 2004; Lang et al., 2010; Jokiel et al., 2015).

The choice of monitoring protocol depends on different characteristics. Main drivers might be related to the socialization of the protocol (training availability and experience of surveyors), needs for data standardization between regions, and objectives of the monitoring program and availability of financial resources. The time required for acquisition and data processing may also influence which protocol is most appropriate (Wilkinson et al., 2003; Brown et al., 2004). Therefore, coral reef researchers and managers are often faced with the challenge of obtaining data while maintaining a compromise between high accuracy, reproducibility, and statistical power, with low cost and time for analysis (Aronson et al., 1994).

Comparisons between PIT, AGRRA, and videotransect (VT) have been previously performed to assess their efficiency (Leujak and Ormond, 2007; Jokiel et al., 2015). The main findings indicate that the protocols based on visual surveys like, AGRRA and PIT, have low repeatability and high variability on benthic cover estimates, when compared to image-based protocols (Carleton and Done, 1995; Brown et al., 2004; Lam et al., 2006; Leujak and Ormond, 2007; Montilla et al., 2020). The use of VT has also shown to provide more accurate estimates on the benthic cover of organisms (Aronson et al., 1994; Leujak and Ormond, 2007; Jokiel et al., 2015). Image-based protocols also produce a permanent record, where species identification and other metrics are obtained under laboratory conditions (Page et al., 2016).

Underwater digital photogrammetry protocols (UWP) with different approaches have recently been used to address changes in the 3D structure associated with natural disturbances (Burns et al., 2015; Peck et al., 2021), assess patterns in the spatial distribution of reef-building corals (Edwards et al., 2017) and reef structural complexity (Burns et al., 2016; Price et al., 2019), and characterize the ecological structure and demographic characteristics of coral colonies (Capra et al., 2017; Edwards et al., 2017; Young et al., 2017; Bianchi, 2019; Lechene et al., 2019; Neyer et al., 2019; Bayley and Mogg, 2020; Burns et al., 2020; Hernández-Landa et al., 2020; Nocerino et al., 2020; Rossi et al., 2020). Results on comparisons between UWP and monitoring protocols to assess reefs characteristics obtained from sites in the Indian and Pacific ocean have been varied. Urbina-Barreto et al. (2021) showed that the LIT overestimates coral cover in comparison to UWP. However, Couch et al. (2021) observed a high consistency of data between UWP and field visual surveys. Considering the advantages and recent integration of underwater photogrammetry to monitor coral reefs, there is a clear need to compare its performance with commonly used protocols. For the Caribbean region, where several standard monitoring protocols are used to assess coral reefs, this has not yet been performed. In this study, we compare the difference in terms of community structure, coral cover, abundance, and species richness estimates, between UWP and simulations of the VT, PIT, and AGRRA sampling designs, using the insular reefs of Cozumel as a case study. These reefs have differences in terms of depth, coral cover, community structure, and structural complexity and can be considered as representative of coral reefs in the region.

2. MATERIALS AND METHODS

The Cozumel Reefs National Park (CRNP) is located 16 km from the coast of Quintana Roo, México (**Figure 1**). The characteristic seascape of the CRNP is a mixture of fringing reefs, patch reefs, and mixed corals on hard calcareous substrate, with algal and seagrass beds, and mangrove areas (Rioja-Nieto et al., 2019). The shallow sublittoral slope tends to be narrow, with the most developed reefs found along the edge of the southwestern insular shelf (Muckelbauer, 1990).

Six fringing reefs (6–14 m depth), distributed in a north to south gradient in terms of increasing reef structural complexity (Fenner, 1988; Muckelbauer, 1990), and abundance and live coral cover of dominant species (Hernández-Landa et al., 2020), were characterized using a UWP (**Figure 1**).

On each reef, photographs were obtained by divers along transects that followed the development of the reef (**Table 1**).

The divers swam at a constant speed 2 m above the average depth of the reef, taking photographs with the self-timer setting of the camera to ensure a high overlap (>80%) across and along images. The obtained images were processed with Agisoft metashape (v. 1.5) to construct orthomosaics and obtain Digital Surface Models. Custom made quadrants of vinyl polychloride (PVC), measuring 0.6 m, were used as a scale constraint in order to get accurate measurements from coral colonies. Vector files based on the orthomosaics were constructed with ArcMap v.10.5 by digitizing all coral colonies with a size >5 cm [for further details, see Hernández-Landa et al. (2020)]. The coral species were identified using the Humann and DeLoach (2002) and Lang et al. (2010), identification guides.

The orthomosaics (three per reef measuring c.a 150 m^2 each) were used as a basis for a surface analysis (UWP) and to simulate transects to obtain data on the hard coral community according to the VT, PIT, and AGRRA monitoring protocols (**Table 1**). For the UWP, a surface area of 380 m^2 was delimited from the orthomosaics in each reef. This area of analysis is considered to be representative of >90% of the hard coral species richness in these same reefs (Hernández-Landa et al., 2020). The percentage of cover of each species, based on the digitized vector files described

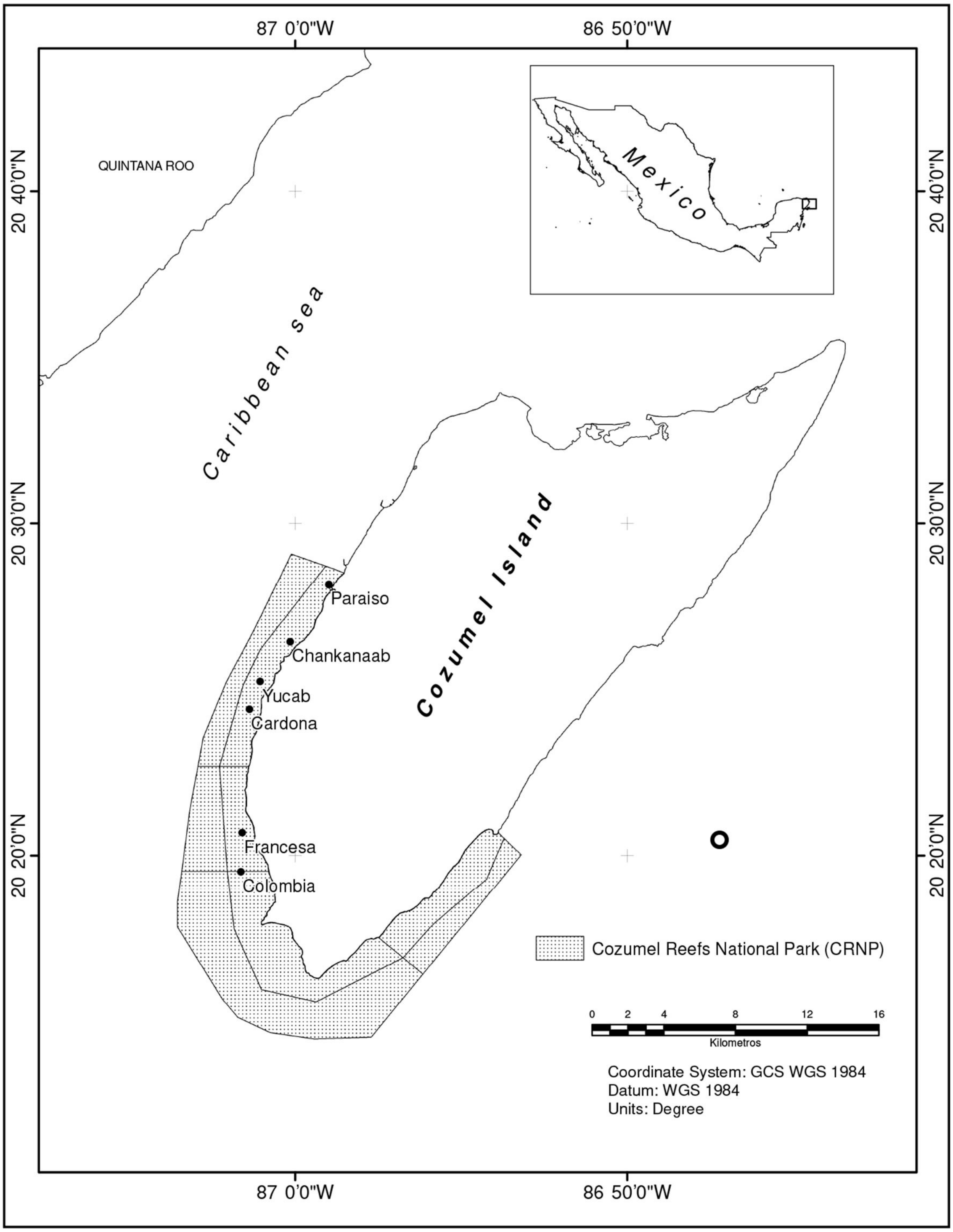


FIGURE 1 | Location of six reefs within the Cozumel Reefs National Park, where comparisons between sampling designs were performed.

above, was estimated as the percentage of the total area surveyed that was covered by a hard coral species (**Figure 2**).

For the VT, two transects (six per reef) on each orthomosaic (0.6 × 29.6 m) were randomly simulated. In order to sample 100 m^2 (Aronson et al., 1994; Leujak and Ormond, 2007), frames were extracted every 0.63 m at a scale that ensured an area covering 60 × 60 cm per frame (**Figure 3**). Thirteen randomly distributed points were selected on each frame, and a spatial

TABLE 1 | Sampling protocols used for benthic communities, underwater digital photogrammetry (UWP), videotransect (VT), point intercept transect (PIT), and Atlantic and Gulf Rapid Reef Assessment (AGRRA).

Protocol	Sampling replicates per reef	Sampling area m^2	Details	References
UWP	3	380	Three plots of 5 × 25.4 m for a total of 380 m^2	Bayley and Mogg, 2020; Hernández-Landa et al., 2020
Video transect (VT)	10	100	Transects of 25 m × 60 cm and evaluation of 13 random points per frame.	Aronson et al., 1994; Leujak and Ormond, 2007
Point intercept protocol (PIT)	1	NA	A 50 m transect over the reef structure with evaluations every 10 cm.	Hill and Wilkinson, 2004
AGRRA	6	NA	Six 10 m transects over the reef structure with evaluations every 10 cm.	Lang et al., 2010

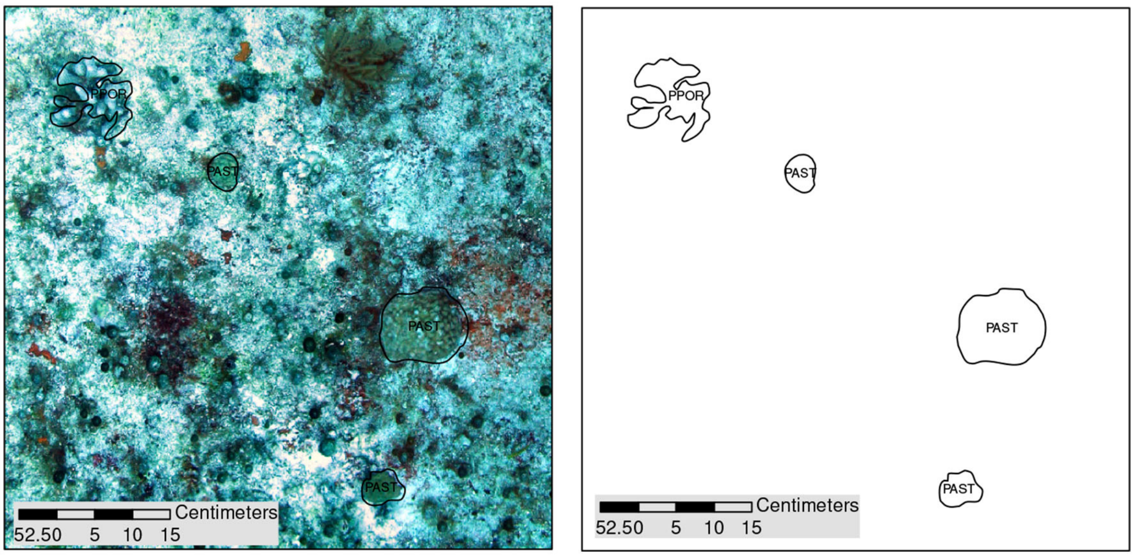


FIGURE 2 | Stony corals from a high-resolution (1.3 mm/pixel) orthomosaic **(left)**. The boundaries of each coral colony **(right)** were digitized and identified (*Porites porites*, PPOR; *Porites astreoides*, PAST), The benthic cover was estimated with the spatial information in each vector on the software Arcmap v.10.5. The code used is in accordance with the AGRRA protocol (see https://www.agrra.org/training-tools/coral-training/).

intersection function with the vector files was used to select coral colonies. The number of points analyzed per frame was chosen considering the average between the analyzed points reported by Aronson et al. (1994) and Leujak and Ormond (2007). The coral cover for each reef was estimated as the percentage of points that intersected with a coral species.

In the PIT, three transects, 16.7 m long (one per orthomosaic), were randomly simulated to survey c.a. 50 m (Hill and Wilkinson, 2004) on each reef. The identity of the substrate intersected by the transect was recorded every 10 cm (**Figure 4**), and coral cover estimated as the percentage of points where a hard coral species was detected.

In the case of AGRRA, six transects per reef (two per orthomosaic), with a 10 m length, were randomly simulated. Coral cover was estimated following the same procedure described for the PIT sampling design.

For all sampling designs, species richness and colony abundance were estimated as the number of species detected or colonies counted in the area (380 m^2 for UWP) or points analyzed (3601 for VT, 500 for PIT, and 600 for AGRRA), considering the representative sample size published in the literature (**Table 1**). For the definition of colony, we followed Loya (1972), where a coral colony was considered a detached set of polyps interconnected by live tissue, regardless of neighboring colonies.

2.1. Data Analysis

The sampling techniques simulations were compared in terms of percentage of cover, species richness, and species abundance. Given the different characteristics in the coral community structure between reefs (Hernández-Landa et al., 2020), each reef was considered as a replica for the analysis.

Generalized linear models (GLM) were used to assess differences on percentage of cover and species richness among monitoring sampling designs. A Gamma and Poisson error distributions for coral cover and species richness, respectively, were assumed (Zuur et al., 2009). The species richness presented overdispersion; thus, SE were corrected using a quasi-GLM

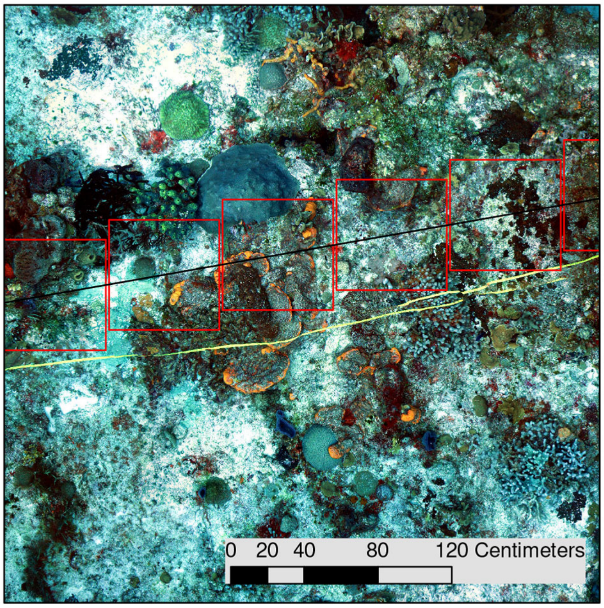


FIGURE 3 | Example of a simulated video transect. The black line is a polyline resembling a transect over the orthomosaic. Each red box represents an extracted frame. The yellow line is the original transect.

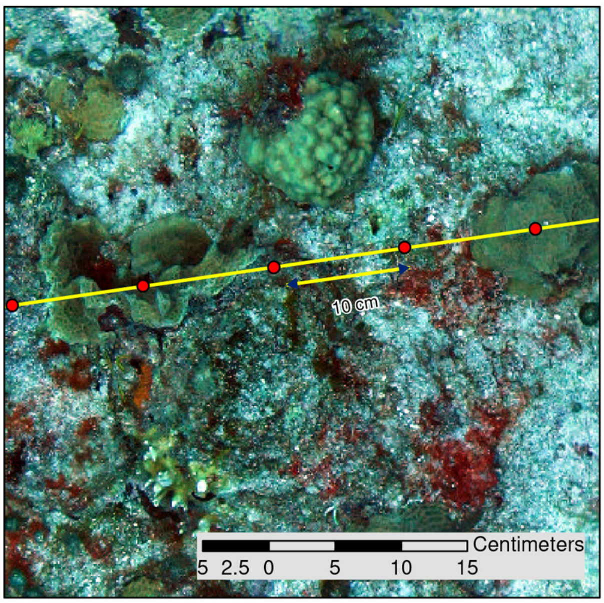


FIGURE 4 | Simulated transect line, where the identity of the substrate was assessed every 10 cm.

model (Zeileis and Hothorn, 2002; Hothorn et al., 2008; Zuur et al., 2009). The models were validated using standard residual diagnostics. A plot of residuals vs. fitted values was used for the assumption of homoscedasticity, and q-q plots of residuals were used to test the residual normality assumption. Species abundance estimates did not accomplish GLM assumptions. Therefore, a generalized estimating equation (GEE) approach was used to compare species abundance among monitoring sampling designs. GEE is similar to GLM but allows for the use of a correlation matrix structure that takes into account the lack of independence of each cluster (Yan, 2002; Yan and Fine, 2004; Halekoh et al., 2006; Zuur et al., 2009). The abundance estimates for each species from the monitoring sampling designs can violate the independence assumption, increasing the risk of type I error. Thus, they were compared among correlation structures (i.e., independence, exchangeable, and ar1) to consider correlation between abundance measures for the same cluster (i.e., each species). The correlation structure with the lowest value of correlation information criterion was the ar1. In all cases, a log link function, and a one-factor ANOVA (Zuur et al., 2009) were used. Community structure characteristics were considered as dependent variables, and the sampling designs were defined as factors. When a significant difference ($p < 0.05$) was observed, a Tukey HSD *post-hoc* multiple comparison test was used to identify differences among sampling techniques simulations (Bauer, 2000). All data were analyzed in R v3.6.1 (R Core Team, 2019).

To identify the species that contributed to 90% of the abundance and cover (dominant species) according to each sampling design, a SIMPER analysis (Clarke and Warwick, 2001), was performed with PRIMER v.7.

3. RESULTS

3.1. Coral Colony Abundance

The average number of colonies observed was 2024 (UWP), 325 (VT), 62 (AGRRA), and 54 (PIT). The values obtained with each sampling design per reef are presented in **Supplementary Table 1**. The UWP recorded a significantly higher mean colony abundance than the other sampling designs ($p < 0.001$) (see **Supplementary Table 2**). VT recorded a higher mean colony abundance than AGRRA and PIT ($p < 0.001$). No significant differences ($p > 0.05$) were observed between AGRRA and PIT (**Figure 5**). The species *Agaricia agaricites*, *Porites porites*, and *Siderestrae siderea* were identified as those with the highest percentage of contribution to abundance in all the sampling designs (**Table 2**). However, important differences on the percentage of contribution between sampling designs can be observed. *Porites astreoides* was not detected as dominant by the VT but was identified in the other survey designs. *Orbicella annularis* was only identified by PIT, AGRRA, and VT. The UWP was the only protocol where the *Eusmilia fastigiata* was identified as a dominant species.

3.2. Coral Cover

The average percent of coral cover obtained was 6.02 (UWP), 8.86 (VT), 10.96 (PIT), and 10.38 (AGRRA). The values obtained with each sampling design per reef are presented in **Supplementary Table 3**. The UWP estimated a lower coral cover ($p < 0.03$) than the other sampling designs (**Figure 6**). No other significant differences were observed ($p > 0.05$; see **Supplementary Table 4**). *Agaricia agaricities* and *Siderestrae*

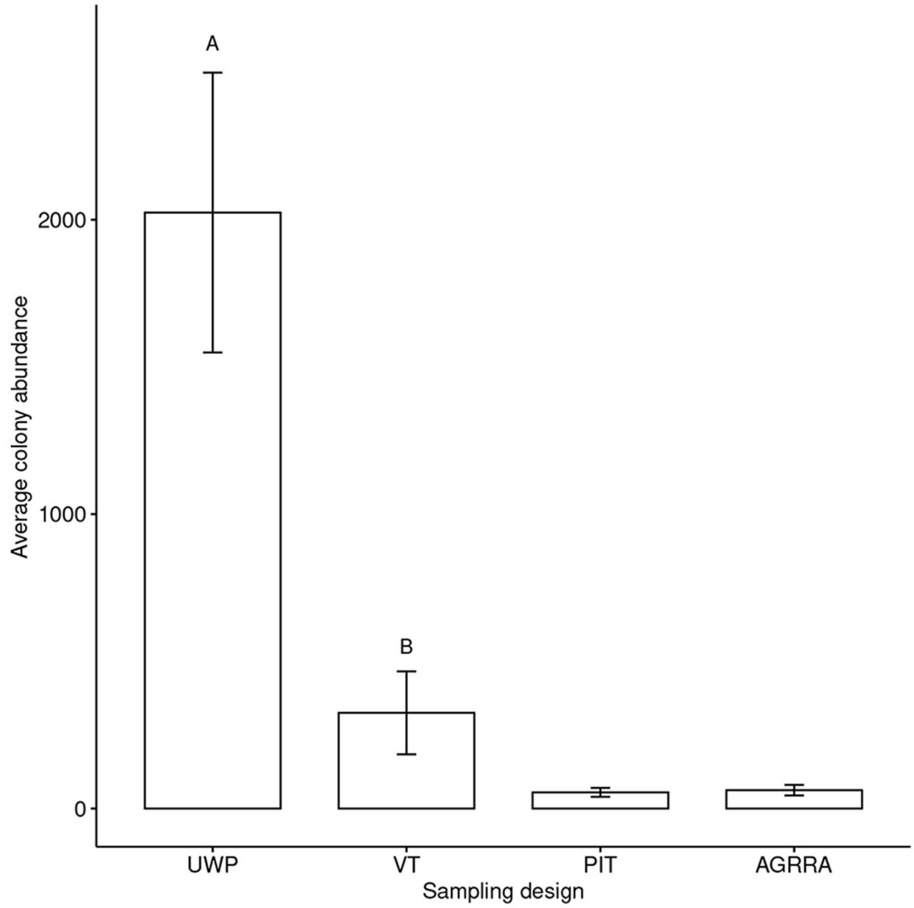


FIGURE 5 | Average colony abundance (±SD) obtained with each sampling design. Underwater digital photogrammetry (UWP), videotransect (VT), point intercept transect (PIT), and Atlantic and Gulf Rapid Reef Assessment (AGRRA). Letters indicate the sampling designs where the average colony abundance had a significant difference ($p < 0.001$).

siderea accounted for the majority of coral cover recorded across methods (**Table 3**). Differences in the species contribution are observed. *Porites astreoides* was considered dominant according to the UWP, PIT, and AGRRA. The species *Agaricia tenuifolia* is dominant for the UWP, VT, and AGRRA. UWP and AGGRA listed the same dominant species *P. porites*, *S. siderea*, and *P. astreoides* (**Table 3**).

3.3. Species Richness

Considering all sampling designs, a total of 31 species were recorded (**Table 4**). The UWP detected more species ($p < 0.001$, **Supplementary Table 5**) than VT, PIT, and AGGRA (**Figure 7**). The species *Dichocoenia stokessi*, *Solenastrea Bournoni*, *Scolymia* sp., *Isophyllia rigida*, *Colpophyllia natans*, and *Manicina areolata*, were only detected by UWP (**Table 4**). With the exception of *O. franksi* and *M. lamarckiana* for species abundance, and *A. tenuifolia*, *P. furcata*, *M. cavernosa*, *O. faveolata*, and *P. clivosa* for coral cover, the observations obtained with UWP showed higher values for the species abundance and lower values for coral cover than the other sampling designs.

4. DISCUSSION

Higher colony abundance, species richness, and lower coral cover estimates were obtained with the UWP. However, all the sampling designs showed a similar capability to identify dominant species in terms of colony abundance and coral cover. The VT, PIT, and AGRRA showed similar coral cover values, which seems to indicate that these commonly used protocols overestimate this metric. The reefs used for the analyses are distributed at different depths and have differences in structural complexity and community structure, representing reef characteristics observed in other regions of the Caribbean.

4.1. Coral Cover, Colony Abundance, and Species Richness

In terms of coral cover, our results are similar to the study of Urbina-Barreto et al. (2021), where underwater photogrammetry provided significantly lower estimates on coral cover than the line intercept protocol. The average percentage of coral cover obtained by the UWP (c.a. 6), is lower than those reported from

TABLE 2 | Dominant species in terms of abundance, identified with a SIMPER analysis by each sampling design.

Protocol	Spp	%	Protocol	Spp	%
UWP	AAGA PAST SSID PPOR EFAS	39.1 22.49 17.45 10.01 2.69	VT	ATEN AAGA PPOR OANN SSID	34.62 28.02 18.41 7.21 6.01
PIT	AAGA PPOR SSID PAST OANN	44.23 18.35 10.92 10.39 7.92	AGRRA	AAGA PPOR PAST OANN SSID	51.71 17.98 9.37 8.06 6.85

Agaricia agaricites (AAGA), A. tenuifolia (ATEN), Eusmilia fastigiata (EFAS), Orbicella annularis (OANN), Porites astreoides (PAST), P. porites (PPOR), and Siderastrea siderea (SSID). Underwater digital photogrammetry (UWP), point intercept transect (PIT), videotransect (VT), and Atlantic and Gulf Rapid Reef Assessment (AGRRA).

TABLE 3 | Dominant species in terms of cover, identified with a SIMPER analysis by each sampling design, the order of appearance indicates the contribution to the total cover.

Protocol	Spp	%	Protocol	Spp	%
UWP	AAGA PAST SSID PPOR ATEN	41.3 17.58 16.20 13.71 4.58	VT	ATEN AAGA PPOR OANN SSID	34.62 28.02 18.41 7.21 6.01
PIT	AAGA SSID PPOR PAST	51.27 20.31 10.76 7.78	AGRRA	AAGA PPOR PAST SSID ATEN	35.82 22.24 20.74 9.99 5.08

Agaricia agaricites (AAGA), Agaricia tenuifolia (ATEN), Orbicella annularis (OANN), Porites astreoides (PAST), Porites porites (PPOR), and Siderastrea siderea (SSID). Underwater digital photogrammetry (UWP), point intercept transect (PIT), videotransect (VT), and Atlantic and Gulf Rapid Reef Assessment (AGRRA).

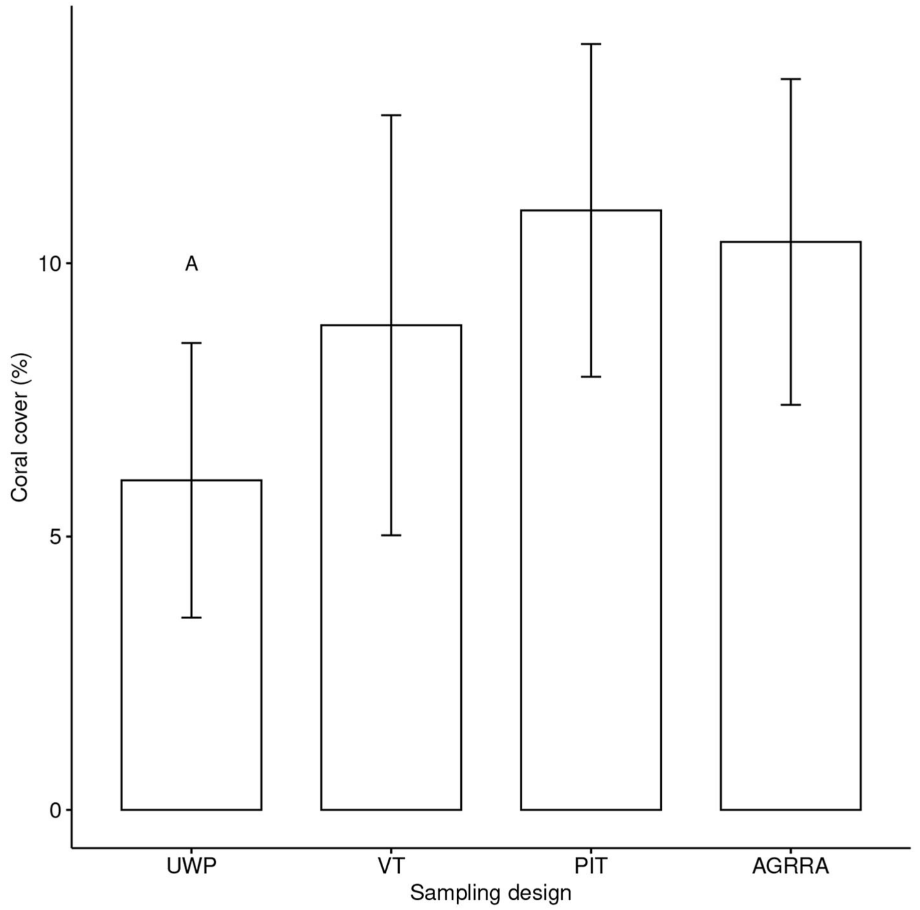


FIGURE 6 | Average percentage of coral cover (±SD) estimated with each sampling design. Underwater digital photogrammetry (UWP), videotransect (VT), point intercept transect (PIT), and Atlantic and Gulf Rapid Reef Assessment (AGRRA). The letter indicates the sampling design where the percentage of coral cover was significantly different ($p < 0.03$).

visual surveys for reefs in Cozumel. Reyes-Bonilla et al. (2014), Barranco et al. (2016), and McField et al. (2018) have reported coral cover values of c.a. 11, 29, and 17%, respectively.

The standardization of underwater photogrammetry protocols needs to be considered. In a recent study, Couch et al. (2021) detected no differences on the estimation of coral

TABLE 4 | Colony abundance for each of the species recorded by the sampling designs.

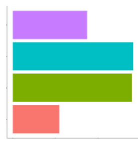
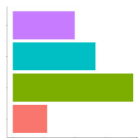
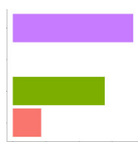
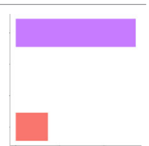
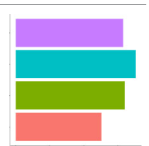
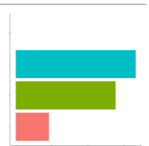
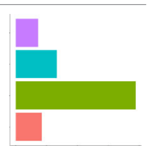
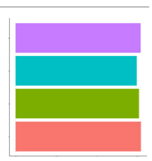
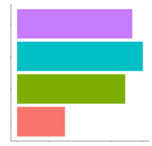
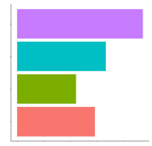
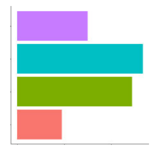
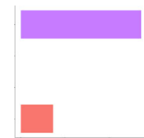
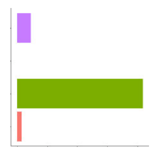
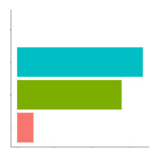
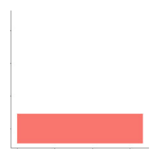
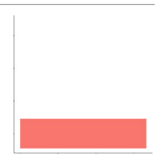
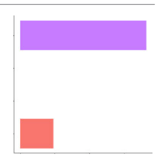
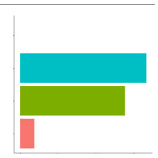
Spp	UWP	AGRRA	PIT	VT	Cover
Agaricia agaricites, AAGA	3898	101	85	386	
Agaricia Humilis, AHUM	298	7	4	22	
Agaricia tenuifoila, ATEN	686	30	35	405	
Agaricia fragilis, AFRA	34	1		8	
Agaricia lamarcki, ALAM	15			6	
Porites porites, PPOR	1,885	58	53	348	
Madracis decactis, MDEC	55	1	1		
Porites furcata, PFUR	103	7	2	8	
Siderastrea siderea, SSID	1,241	45	41	186	
Montastraea cavernosa, MCAV	343	11	9	68	
Orbicella annularis, OANN	660	31	30	202	
Orbicella faveolata, OFAV	62	4	5	52	
Porites astreoides, PAST	1,797	44	40	165	
Orbicella franksi, OFRA	10			10	
Favia fragum, FFRA	79	3		2	
Stephanocoenia intersepta, SINT	2	1	1		
Dichocoenia stokesii, DSTO	7				
Solenastrea bournoni, SBOU	7				
Mycetophyllia sp., MYCE	8			2	
Meandrina jacksoni, MJAC	4	1	1		

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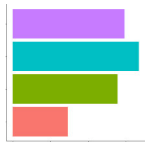
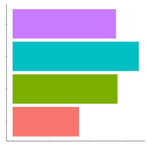
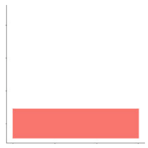
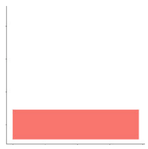
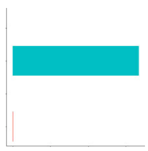
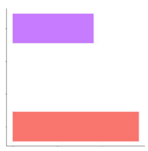
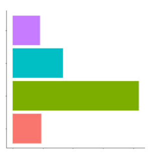
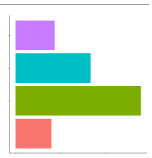
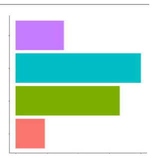
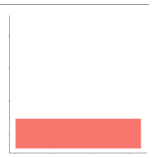
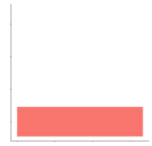
TABLE 4 | Continued

Spp	UWP	AGRRA	PIT	VT	Cover
Meandrina meandrites, MMEA	40	2	2	13	
Dendrogyra cylindrus, DCYL	8	1	1	6	
Isophyllia rigida, IRIG	14				
Manicina areolata, MARE	4				
Mycetophyllia lamarckiana, MLAM	1		1		
Pseudodiploria clivosa, PCLI	15			2	
Diploria labyrinthiformis, DLAB	33	3	1	4	
Eusmilia fastigiata, EFAS	445	10	5	19	
Siderastrea radians, SRAD	329	6	6	17	
Colpophyllia natans, CNAT	1				
Scolymia sp., SCOL	1				

(Continued)

Relative coral cover range in the graphs is between 0 and 2.83. The colors represent each protocol. Underwater digital photogrammetry (UWP), point intercept transect (PIT), videotransect (VT), and Atlantic and Gulf Rapid Reef Assessment (AGRRA).

cover and other metrics (e.g., species richness, adult colony density, and average colony diameter) between an underwater photogrammetry protocol and in water visual surveys. This seems to be related to the area of analysis used in that study (60 m^2). It has been reported that this same surveyed area with photogrammetry only represents 55% of all benthic features (Lechene et al., 2019). Furthermore, Hernández-Landa et al. (2020), determined that for the CRNP reefs an area of c.a. 380 m^2 is needed to obtain representative species richness data.

The species *A. agaricites*, *P. porites*, and *S. siderea* were identified in all cases as dominant and have been reported as typical of the Caribbean region (Reyes-Bonilla et al., 2014; Barranco et al., 2016; González-Barrios and Álvarez Filip, 2018). Other species such as *P. astreoides* and *A. tenuifolia* were also considered important in most of the sampling designs. For UWP, the species *E. fastigiata* was identified as dominant. This is an uncommon and small sized species (colonies about 20 cm in adult phase) (Veron J.E.N. and L.M., 2016; Horton et al., 2021), which suggests this sampling design to be sensitive to detect species with similar morphological characteristics and colony size. AGRRA, PIT, and VT are known to underestimate colonies that are too small or rare (Leujak and Ormond, 2007; Jokiel et al., 2015; Facon et al., 2016). VT was the only protocol that identified the massive species *O. annularis* as dominant in terms of cover. With big sized massive species, the area of the colonies can exceed the size of the evaluated frame. In this case, all the points distributed on the frame detect the same colony, but are assumed to belong to different ones (Bennett et al., 2016; Page et al., 2016). If these types of colonies are recurrent in the transect band, the proportions are prone to generate estimates that differ from the true values (Hill and Wilkinson, 2004). This can also occur with AGRRA and PIT when the diameter of the colonies exceeds c.a. 20 cm (Leujak and Ormond, 2007). For the UWP, it is important to consider local ecological characteristics, and maintain an homogeneous definition of a colony. The latter is particularly important, as an increase in the number of colonies could be related to partial colony mortality and the fission and fragmentation of colonies as a result of disturbance (Hughes and Jackson, 1980; Jaramillo González and Acosta, 2016).

The UWP recorded six uncommon species that were not detected by the other sampling designs. Five of these, *D. stokesii*, *S. bournoni*, *M. areolata*, *Scolymia* sp., and *I. rigida*, are small sized with adult colonies measuring c.a. 20 cm (Veron J.E.N. and

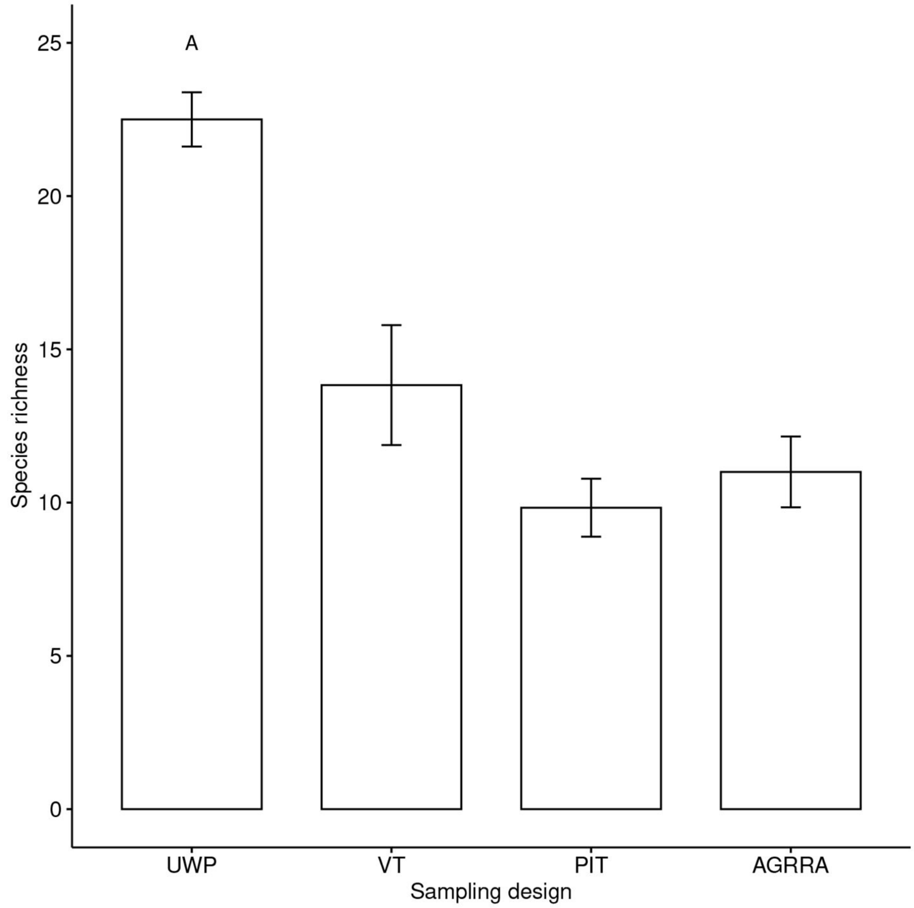


FIGURE 7 | Average number of species (±SD) obtained with each sampling design. Underwater digital photogrammetry (UWP), videotransect (VT), point intercept transect (PIT), and Atlantic and Gulf Rapid Reef Assessment (AGRRA). UWP recorded the highest number of species. The letter indicates a significant difference ($p < 0.001$).

L.M., 2016; Horton et al., 2021) *C. natans* is a massive species (Torruco et al., 2021). Considering the large area of analysis and the detailed colony digitization on the orthomosaics, the species richness based on the UWP is not affected by species traits such as colony size or abundance.

4.2. Comparisons Between Monitoring Protocols

Point Intercept Transect and AGRRA are suitable for coral reef characterization due to their ease of use and fast data availability (Carleton and Done, 1995; Hill and Wilkinson, 2004; Leujak and Ormond, 2007; Facon et al., 2016). Also, in sites with a high structural complexity (i.e., spurs and grooves), PIT performs better given the orthographic projection to a 2D that is needed for image-based protocols (Nadon and Stirling, 2006). However, these protocols need well-trained experienced divers for *in situ* species identification and data collection. The ecological characteristics of the sampling sites (e.g., sites with low coral coverage or high structural complexity) can also have an effect on the estimates based on the data obtained from these sampling designs. In sites with low coral cover, such as most of the sites sampled in here (and arguably in the Caribbean region), the obtained data tend to have low representativeness and be less accurate (Molloy et al., 2013). Furthermore, the contour effect of the colonies, where transect lines follow the edge of large coral colonies, can also affect data collection (Lam et al., 2006).

Video Transect is a cost-effective protocol that can reduce the economic costs of data acquisition for large areas vs. PIT and AGRRA (Aronson et al., 1994). This monitoring protocol has the necessary inputs to adopt a photogrammetric approach by applying small adjustments, and should be explored. Like UWP, VT generates a permanent record that can be later verified. However, the taxonomic identification on some benthic groups (e.g., macroalgae and sponges) can be limited by the images resolution (Aronson et al., 1994; Carleton and Done, 1995).

Underwater digital photogrammetry is a rapid survey protocol for large areas without the need for trained personnel in species identification (Chirayath and Instrella, 2019; Lechene et al., 2019; Price et al., 2019; Bayley and Mogg, 2020; Hernández-Landa et al., 2020). This protocol allows extracting not only cover and community metrics but also important demographic information on the size of the colonies and the spatial relationships in the benthic community (Edwards et al., 2017; Hernández-Landa et al., 2020). With the use of UWP, accurate 3D, and digital elevation models can also be produced. Furthermore, establishing permanent markers on the substrate can allow precise long-term monitoring of coral common (e.g., coral cover and species richness), and marginally explored characteristics (e.g., colony size variation and spatial distribution, changes in 3D metrics over depth, or disturbance gradients) of the reef community at large spatial scales. This will increase our understanding of the processes that shape coral reef communities. The image processing in UWP and subsequent data analysis can be time-consuming (2–3 months for a full time experienced person) or expensive to implement considering the need of specialized hardware and software. However, there are several options for the adoption of free or proprietary software (Leon et al., 2015; Lechene et al., 2019) and the use of affordable devices such as the Jetson Nano GPU NVIDIA (Barba-Guaman et al., 2020). For the data analysis, automated species identification and artificial intelligence are being developed (Chirayath and Instrella, 2019; Pavoni et al., 2020; Yuval et al., 2021) and may reduce the time needed to obtain valuable information.

Underwater photogrammetry protocols are increasingly being used to assess coral reefs. To our knowledge, at least six studies using underwater photogrammetry for coral reef monitoring have been published. The protocols mainly differ in the area sampled for analysis, ranging from 60 to 1,655 m^2, but are similar in image acquisition procedure, cameras utilized, image processing algorithms, fieldwork environmental conditions during data collection (clear water, shallow sites), use of internal control points, and the colony data processing (Palma et al., 2017, 2019; Lechene et al., 2019; Hernández-Landa et al., 2020; Couch et al., 2021; Urbina-Barreto et al., 2021). UWP relies on the surface analysis of the benthic substrate, and obtained metrics seem to be biased by the area considered. More studies are needed to determine the representative sampling area for photogrammetric analysis in the different regions where coral reefs distribute. This will ensure that direct comparisons in different regions, can be made between long-term monitoring programs. Our results also suggest that commonly used monitoring protocols in the Caribbean are overestimating coral cover, and underestimating species richness and colony abundance with the "standardized" sampling effort, and this needs to be further explored. Finally, it is important to consider that the data obtained for the VT, PIT, and AGGRA protocols presented in here were not obtained under field conditions. Therefore, circumstances that can have an impact on the quality of the data acquired with these sampling designs such as current effects, availability of time to conduct the surveys, and *in situ* species identification, among others, are not considered.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

EB-F, RR-N, and RH-L: conceptualization, methodology, validation, writing—review and editing, and writing—original draft preparation. EB-F, RR-N, and ET-I: formal analysis. EB-F: investigation, visualization, and software. RR-N: supervision, project administration, resources, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2021.722569/full#supplementary-material

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