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research paper

Comparison of video camera sled with diver surveys for queen conch *Lobatus gigas* density estimates in the west coast of Puerto Rico

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ABSTRACT.—Queen conch *Lobatus gigas* is one the most important fishery species in the Caribbean. Currently, queen conch harvest is prohibited in the Exclusive Economic Zone (EEZ) in Puerto Rico. Since 1996, abundance estimates in Puerto Rico have been conducted by scuba divers at intervals of 5 yrs. Yet diver surveys are limited by depth and time. In contrast, underwater video or camera surveys are not constrained by these factors and also provide a permanent photo record of observations. We conducted a survey of queen conch density on the western shelf of Puerto Rico in 2016 using two different methods: divers and a camera sled. Divers surveyed eight transects of 2–3 km using diver propulsion vehicles and standardized, historical methods. The camera sled was fitted with a digital camera, synchronized strobe lights, and paired lasers, and was towed along the dive transects several days later. Conch densities (conch ha^{-1}) estimated with the camera sled were significantly higher than those estimated by diver survey methods, while mean length was smaller. Both results were driven by the higher selectivity of the sled method for smaller conch. These results may lead to further applications or development of sled survey techniques, and improved data collection and analysis that can be used for management of queen conch in the Caribbean.

Queen conch, *Lobatus gigas*, is one of the most important fishery species in the Caribbean, where its fishery can be traced back to pre-Columbian times (Davis 2005). These gastropods exhibit two types of migrations: (1) ontogenetic migration of large juveniles to deeper water and (2) adults to shallower areas for spawning (Medley 2008). Queen conch migrate inshore during the months of mid-May to mid-November to spawn, resulting in large numbers of individuals present in easily fishable waters, which makes them an easy target for fishers (Appeldoorn 1993). Unlike in many fisheries, the targeted fishing of spawning aggregations significantly decreases the density of adults; low density overall has been linked to a significant Allee effect (Stoner and Ray-Culp 2000, Stoner et al. 2012) and since conch are both slow-moving and require copulation, this could reduce reproductive output (Appeldoorn 1995). Management of queen conch is difficult due to the absence of reliable information for stock assessment (SEDAR 2007, Baker et al. 2016) and the inadequacy of landings and fishing effort data reported. For example, only commercial fishers are required to report landings in Puerto Rico (Matos-Caraballo and Agar 2008) and the greater Caribbean (Salas et al. 2007). Regulations and seasonal closures are imposed, but the lack of enforcement and compliance directly influences the amount and quality of landings data needed for adequate stock assessment (Salas et al. 2007).

Queen conch landings are second only to spiny lobster in Puerto Rico (Matos-Caraballo 2011). Landings of queen conch in Puerto Rico peaked in the 1970s, resulting in overfishing of the population (Appeldoorn 1991, Baker et al. 2016). The queen conch fishery is considered overfished, and mean densities have been reported as low as 7.5 conch ha^{-1} (Mateo et al. 1998). In 1992, queen conch were declared commercially threatened and became protected under Appendix II of the Convention on International Trade in Endangered Species (Pittman et al. 2010). Since 2004, both recreational and commercial queen conch harvesting has been prohibited in the Puerto Rico Exclusive Economic Zone (EEZ; SEDAR 2007, CFMC and NOAA 2013). Conversely, the fishery in Puerto Rico territorial waters remains open but is managed under size limits, daily commercial and recreational quotas, and a seasonal closure from 1 August to 31 October (CFMC and NOAA 2013).

Due to overfishing, queen conch populations in many areas have been depleted in shallow water (<15 m, and in some cases <25 m; Davis 2005, Ehrhardt and Valle-Esquivel 2008), and fishing effort has been redirected to deeper waters (FAO 1993, CFMC and NOAA 2013). This also influenced fishing practices, which evolved from snorkeling in shallow water to setting nets and scuba diving in deeper water. Deeper populations of queen conch can be found around mesophotic reefs (>30 m; Garcia Sais et al. 2012), and these deep water populations are hypothesized to serve as a source of recruitment for shallow water populations (Garcia-Sais el al. 2012, Boman et al. 2019, *but see* Baker et al. 2016).

To improve management of the queen conch fishery, the Southeast Area Monitoring and Assessment Program-Caribbean (SEAMAP-C) has been conducting fisheries-independent surveys for conch density and size/age structure in Puerto Rico and the US Virgin Islands since 1997 (Baker et al. 2016). Diver-based surveys are limited to waters <30 m and, therefore, may not encompass the entire depth range of the queen conch stock. In addition, traditional open circuit scuba diving constrains the time available for each survey (i.e., about 45 min at 24 m, or until no decompression limit is reached) and the number of dives that can be performed in a day. Nevertheless, diver-based fishery-independent surveys form the basis for assessing stock status throughout the Caribbean (e.g., Berg and Glazer 1995, Aiken et al. 2006, Singh-Renton et al. 2006, Kough et al. 2017, Doerr and Hill 2018), and this is particularly true in Puerto Rico (SEDAR 2007). In the SEAMAP protocol, divers use diver-propulsion vehicles (DPVs) to conduct parallel strip transects, where all conch are counted, estimated to length, and adults binned into age classes. Density and size estimates obtained this way would have similar biases to those obtained using towed divers (e.g., Berg and Glazer 1995, Kough et al. 2017). The most recent queen conch

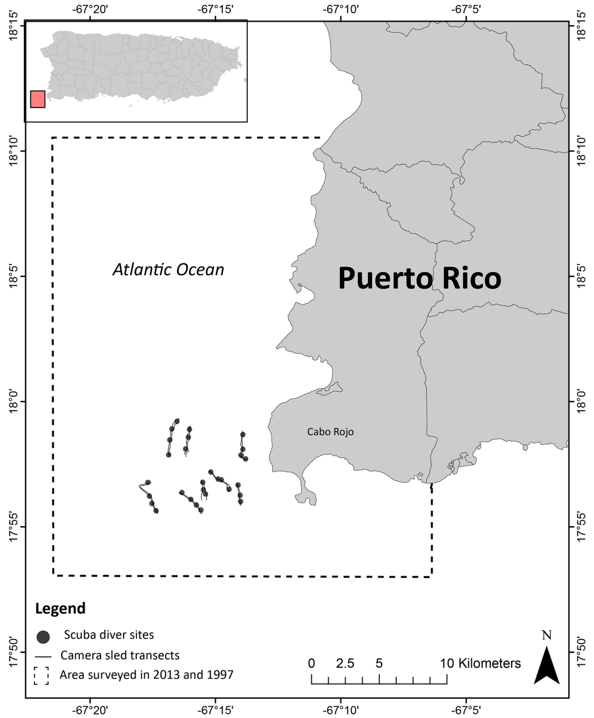

Figure 1. Sampling sites map. Sampling occurred during the months of October–December 2016. Dashed line encloses the area surveyed in 2013 and 1997. Grey circles represent scuba diver transect endpoints and solid lines represent the camera sled tracks.

survey for Puerto Rico was conducted off the southwest corner of the island in 2013 (Baker et al. 2016). Conch densities observed in 2013 averaged 14.4 conch ha^{-1}, which was a significant increase from 8.5 conch ha^{-1} observed in 1997, but not statistically different from densities from more recent surveys (Mateo et al. 1998, Baker et al. 2016). In this study, we tested the use of a video camera sled as an alternative tool for estimating density, size, and age class of queen conch in Puerto Rico. We additionally conducted surveys following the SEAMAP protocol, as used in all previous Puerto Rico surveys, to have a standardized and locally relevant methodology for comparison to diver surveys (Baker et al. 2016). Sled surveys and diver surveys were conducted at the same time, with the sled survey tracks overlain on those of the diver surveys. Two hypotheses were tested: (1) conch density and size/age structure estimates produced by the camera sled are similar to those produced by divers, and (2) camera surveys can be used to accurately measure conch underwater.

METHODS

Sampling sites were selected from the 2013 queen conch population survey areas (Baker et al. 2016). Transects were located in the southwest region of Puerto Rico, around 3–10 km from the municipality of Cabo Rojo (Fig. 1). Initial coordinates of each transect were randomly distributed in preferred substrate including sand, silt, bare rubble or rubble with algae, and seagrass. We avoided conducting any transects on hard bottom, such as corals or pavement, to prevent damage to the environment and equipment while using the camera sled.

Scuba Diver Transects.—A total of eight transects composed of 21 segments were surveyed off the coast of Cabo Rojo, Puerto Rico (Fig. 1). Each line in the figure represents a sequence of three or four diver segments, resulting in eight final transects that the camera sled could replicate. Methods for diver surveys followed the SEAMAP survey method described by Baker et al. (2016). Divers were trained to estimate conch size (Rooker and Recksiek 1992, Yulianto et al. 2015) and age using an established reference collection and published age classes (Appeldoorn et al. 2003). Each diver was required to pass a test for accuracy and precision of measurements. The dive protocol was practiced to proficiency with all participating divers; two lead divers were experienced in this method from participating in the 2013 survey. Diver propulsion vehicles were used to maintain direction and speed, and to maximize area covered during the survey.

Each dive transect consisted of a maximum of four consecutive segments, where a segment represents one dive. The starting point of the first segment was selected based on the habitat requirements, and subsequent segments were aligned so that the end of one segment would serve as the starting point for the next segment, following the same heading. The transect direction for dive surveys was selected to follow the direction of the current, which is a prevailing north or south flow. The heading was changed only if divers encountered unpreferred habitat (reef) or depths greater than 30 m, at which point the dive was terminated or redirected if possible. Only in those instances, the next segment would then start at the original starting coordinates, heading in the opposite direction (sometimes into a mild current) but maintaining the line of sequential segments. The surveys were performed in this way to allow for one continuous transect and relatively straight north or south direction that we would attempt to replicate with the towed camera sled. Camera sled surveys were performed no more than two days after dive surveys.

The diver survey incorporated paired visual census using both divers on DPVs maintaining the same heading and speed. One diver towed a surface marker buoy (dive flag with GPS unit set to track), while the second diver maintained the compass heading. The surface marker allowed a chase boat to follow the divers and verify GPS coordinates and heading. During the survey, divers recorded habitat type and depth at the start of the transect, and recorded changes in these features when encountered. Divers followed the compass heading, surveying for conch within a 4 m width interval with no overlap between divers. The maximum survey time was 45 min or until the no decompression limit was reached. Thus, transects varied in length based on bottom time and current speed.

As conch were encountered, divers stopped just long enough to visually estimate siphonal length (to the nearest cm), using their hands as a length guide (i.e., distance from thumb to end of fifth finger when extended), and recorded age-class along with the depth and habitat encountered following the previous survey criteria (Baker et al. 2016). Any copulation or egg-laying was also recorded. Age classes were documented as juvenile (J), newly mature adult (NMA), adult (A), old adult (OA), and very old adult (VOA), which were based on shell appearance and lip thickness (Appeldoorn et al. 2003). We followed Appeldoorn et al.'s (2003) description of the age classifications

Figure 2. The camera sled main parts include: (A) camera housing, (B) strobe lights, and (C) onboard computer.

for both divers and camera annotators. In brief, the age classes are characterized as follows: (J) no flared lip; (NMA) thin flared lip, tan and clean periostracum, no color on underside of lip; (A) fully formed flared lip, shell starting to show signs of minimal to moderate erosion, periostrocum is tan with some signs of colonization, lip underside white color and pink inside; (OA) outer lip eroded, no periostracum, spines eroded, lip underside is grey color with dark pink inside of shell; and (VOA) thick, perhaps square-shaped lip with flare eroded, perhaps completely, outer shell very fouled and eroded, underside is usually completely eroded and interior is dark pink.

At the end of the survey, divers recorded end time, depth, and habitat. The diver towing the dive flag reeled the buoy directly overhead and signaled to the boat that the dive had concluded by pulling on the line to submerge the flag in a rhythmic pattern visibly different from normal wave activity. The boat then approached the flag and recorded the GPS coordinates, after which a weighted line was dropped to mark the starting point for the next dive team.

The overall length of each transect was measured using ArcGIS (version 10.2.2). Planar measurement was used to calculate the length of each segment, and the segment lengths were summed to calculate the total length of each transect. Area surveyed was calculated by multiplying transect length by transect width of 8 m, representing the sum of two divers 4 m-wide transects. Density of queen conch at each transect was calculated by dividing the total number of queen conch observed by the area surveyed.

Camera Sled Transects.—The camera sled (approximately 2 m long × 1 m wide × 1.5 m high) was composed of an aluminum frame (AquaLife, Kodiak, Alaska) to be lightweight and easily transported (Fig. 2). It included a down-facing camera (Point Grey Research, Inc. Zebra2 5.0 MP 2448 x 2048 at 25 FPS with High Definition-Serial Digital Interface, Sony ICX625 CCD) that covers a field-of-view of 1 m.

Figure 3. Camera sled laser calibration. Nine conch were distributed in different locations to compare length estimated with the lasers and the caliper. Laser dots in the center of the image are 10 cm apart.

Lighting for the camera sled was enhanced by three synchronized strobes (Fisheries Research Instrumentation, Seattle, Washington). Each strobe contained four Bridgelux BXRA-C2002 LED arrays.

The camera sled was towed at the slowest achievable speed from the R/V Sultana (University of Puerto Rico, Mayagüez, Dept. of Marine Sciences) at an average speed of 2–3 kt (1–2 m s^{-1}) and was operated from the boat via laptop computer, which displayed images in real time. The image frame covered an area of about 0.7 m^2 capturing digital photographs at 5 frames s^{-1} that included 10 cm laser marks on the images allowing for conch size estimation (Figs. 3 and 4). The 10 cm lasers were calibrated for accuracy estimates. The camera sled tracks were constantly monitored to avoid reef habitat. The selection of sites and heading for the sled were chosen to mirror the diver transects without encountering reefs, sharp changes in direction, or perpendicular currents pushing the sled off course. Transect start and end points were corrected by estimating the horizontal sled layback from the tow cable length and subtracting it from the vessel GPS locations, in the direction of tow (Cruz-Marrero et al. 2019). Each sled transect was defined by combining contiguous diver survey segments forming a seamless line that the sled could subsequently follow in order to overlap the diver survey area as close as possible. Since the two techniques covered different transect widths, the camera sled was towed both north and south, which created two lines parallel to the diver transects in order to cover a wider area (Fig. 1). If a coral reef (soft or hard) was encountered, the position of the sled was changed to avoid any harm to the environment.

Camera-Laser Calibration.—Conch observed in camera images were measured by comparison to the paired laser dots. Conch were measured when lasers were present in the frames. In some instances, lasers are not visible in frames due to refraction or poor image quality. In those cases, the observed conch could not be

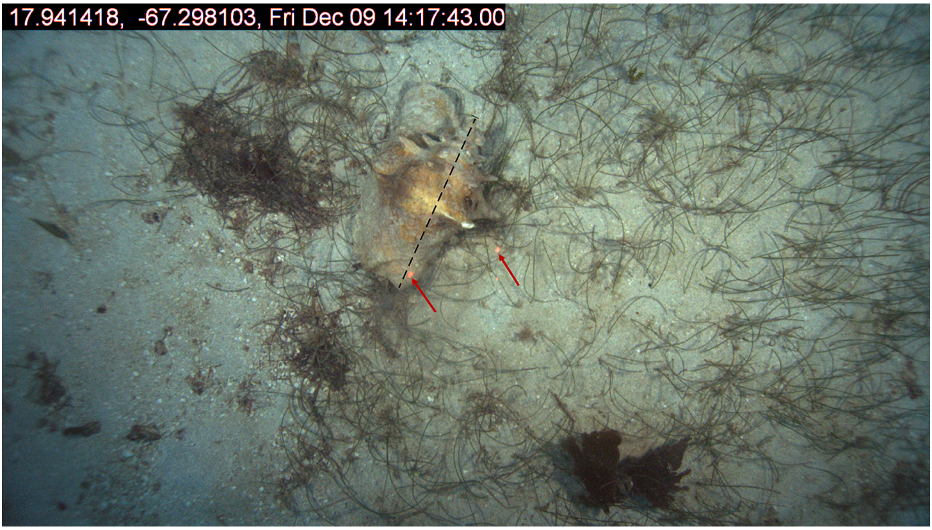

Figure 4. Queen conch image taken with the camera sled. Arrows show the 10 cm lasers, and the dashed line is the siphonal length; latitude and longitude are in the top corner with UTZ time and date.

measured. To determine the accuracy of conch measurements with the lasers, we compared conch siphonal lengths to estimates made using laser calibrated photos. Nine conch were selected for the calibration test, ranging in size from 8.9 to 27.0 cm (Fig. 3). Each conch was premeasured to the nearest 1 mm using calipers, and the size was marked inside the shell for identification. We placed the conch in two random underwater arrangements and repeated this for a total of 18 conch measurements, while a diver moved the conch in different positions in the camera frame to check for distortions. The conch in the still images were measured using ImageJ (Image Processing and Analysis in Java Software).

Image Annotation.—A total of 201,000 images were annotated by two different viewers. Viewers were trained to correctly identify the targeted species of conch, *Lobatus gigas*, differentiate between dead and live conch, and use the measurement tools (Image J). Viewers were first trained with an example dataset to build precision and accuracy and to reduce variability between the two viewers. Conch were distinguished as dead or alive by noting shell coloration, shell damage caused by the extraction of the organism, shell surface erosion, adjacent queen conch tracks, and the position of the shell (i.e., upside-down conch were considered dead; Boman et al. 2016). Conch were counted if alive and if three quarters or more of the shell was in the frame including the spire (soft tissue extraction is done in the spiral area). If the spire is not observed in the image, conch were not considered live. Conch were also classified into age classes using visual estimates of shell condition following the diver guidelines (Appeldoorn et al. 2003, Baker et al. 2016). Images for the first four transects were observed and processed by two viewers to estimate bias in the measurement/age estimation process. The remaining four transects were annotated with a combination of the two viewers. The habitat type was subjectively classified as sand, rubble, seagrass (*Thallassia* sp., *Halophila* sp., *Syringodium* sp.), and algae

Table 1. Data from camera sled survey transects 1–4, including conch counts, mean length of conch (cm), standard deviation of conch length, and density (conch ha^{-1}) for viewers 1 and 2.

Transects	Viewer 1				Viewer 2			
	Conch	Length	SD	Density	Conch	Length	SD	Density
1	76	11.69	4.18	198.14	63	11.39	4.18	164.24
2	167	11.51	4.27	343.89	142	19.93	4.96	292.41
3	132	12.78	5.06	332.07	119	12.33	4.96	299.36
4	86	13.45	4.36	161.69	82	13.23	4.27	154.17

cover. Habitat was visually classified using the two most common substrata in the selected frame, e.g., sand as primary habitat and algae cover as secondary, which would be annotated as sand, algae cover.

Statistical Analysis.—Conch densities were compared between diver and sled transects using a paired sample *t*-test assuming equal variances when variances showed no significant differences. Analysis of variance was used to analyze differences between age group densities. For the calibration experiment, actual conch measurements were compared to size estimated from test images using a paired *t*-test. Conch measurements from the transect images were compared between viewers using a *t*-test (for all measurements) or paired *t*-test (for conchs from matched images).

Results

Conch Counts and Laser Measurements.—Viewers counted a total of 461 conch (viewer 1) and 406 conch (viewer 2) from sled transects 1–4 (Table 1). Both viewers measured conch using the camera sled 10 cm laser as a reference. Viewer 1 measured a total of 378 conch from 461 observed. Viewer 2 measured 360 conch from 406 observed. A total of 319 observations matched between viewer 1 and 2. A Paired Student's *t*-test showed no significant difference between the matched measurements (Paired *t*-test: $t = 1.6567$, df = 319, $P = 0.098$). There was also no significant difference between the two viewers' combined measurements using both matched and unmatched lengths (two sample *t*-test: $t = 0.6565$, df = 736, $P = 0.5116$). Conch measurements using the sled lasers were not significantly different from measurements made with calipers (Paired *t*-test: $t = -1.6192$, df = 16, $P = 0.1249$).

Table 2. Comparison of camera sled and scuba diver surveys including number of conch observed per transect, area surveyed (ha), and density (conch ha^{-1}).

Transects	Camera Sled			Scuba Divers		
	Conch	Area	Density	Conch	Area	Density
1	76	0.384	198.14	146	1.57	96.97
2	167	0.486	343.89	189	1.75	102.49
3	132	0.398	332.07	191	2.26	129.61
4	86	0.532	161.69	122	2.04	63.57
5	83	0.646	128.51	109	1.71	62.30
6	104	0.418	248.82	164	2.13	113.57
7	80	0.544	146.96	120	2.33	58.69
8	45	0.364	123.62	152	1.49	81.76
Combined	773	3.772	210.46	1,193	15.29	88.62

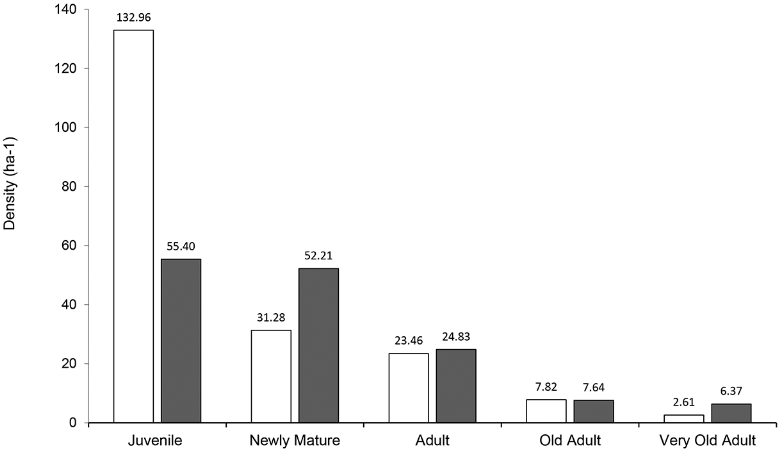

Figure 5. Density (conch ha^{-1}) within each age class estimated by camera sled (white bars) and scuba divers (grey bars). Overall density above each bar.

Area Surveyed and Conch Density Estimates.—A total of 1193 and 773 conch were counted by divers and the camera sled, respectively (although over different total areas surveyed; Table 2). Conch density values estimated by the camera sled ranged from 122.6 to 343.9 conch ha^{-1}, with an overall mean of 210.5 conch ha^{-1} (SE 31.3), and divers' estimates ranged from 58.7 to 129.6 conch ha^{-1}, with an overall mean of 88.6 conch ha^{-1} (SE 9.3; Table 2). Density estimated by camera sled and diver transects were significantly different (paired sample t-test: $t = -5.05$, df = 7, $P = 0.001$). Juveniles and newly mature adults comprised 82.36% of conch observed with the camera sled, and 61.92% of conch observed in the diver surveys. The other age classes contributed less to the overall density estimates (Fig. 5). The estimated length of conch ranged from 5.5 to 25.7 cm in the sled survey images, and 3.0 to 30.0 cm in the diver survey (Fig. 6). There was a significant difference between the mean length measured by divers [mean 16.93 cm (SE 0.15)] and from the sled images [mean 12.91 cm (SE 0.18); two sample t-test: $t = 16.96$, df =1506.7, $P < 0.0001$; Fig. 6]. Estimated length within age class was also less for the sled camera than diver-estimated lengths (two-way ANOVA, $P < 0.0001$; Fig. 5). There was no significant difference between age class distribution obtained by both techniques (ANOVA, $P > 0.05$).

Discussion

The greatest differences found between the two methods are the higher density and the shift in length-frequency distribution to smaller sizes using the sled camera method. The most important factor explaining these differences is the difference in selectivity of the two methods, i.e., their ability to detect small individuals. In Figure 6, conch are not fully selected to diver observation until reaching at least the 16–20 cm size class, whereas full selection using the sled may occur as small as the 6–10 cm size class. This is also supported by the proportional declines in the larger size classes, which is similar for the two methods. Accurately detecting smaller conch is important for determining critical juvenile nursery areas, for the early estimate of

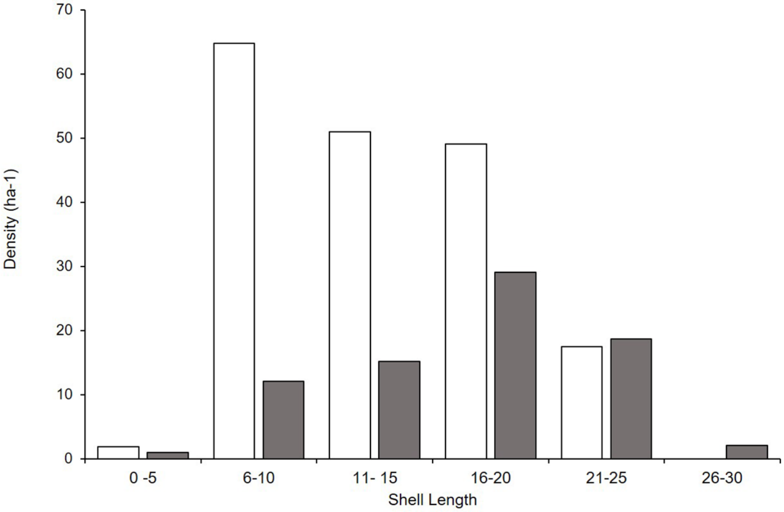

Figure 6. Length distribution of queen conch densities by camera sled (white bars), and scuba divers (grey bars). Shell length in cm.

recruitment strength (especially when surveys are only conducted periodically), and for interpreting overall density. In this case, the higher density estimate obtained within the sled transects can be entirely attributed to detecting a much higher percentage of smaller conch.

Two reasons could contribute to the poorer selectivity of small conch in the diver surveys. First, while the use of the diver propulsion vehicles (DPVs) helped cover more area, they were also a distraction, because divers had to maintain a compass heading and drive the vehicle while looking for conch. Second, the ability to visually detect conch declines with distance from the observer (especially if conch are hidden by tall seagrass or half-buried in the sand), so transects with a width of 4 m may be too wide to be covered effectively.

Given the accuracy of sled-based shell length estimates, there is some evidence suggesting that divers may be overestimating length. While no direct comparison of diver vs sled-based length measurements was made, the divers recorded 2.7% of their individuals within the highest length class, while none were found from the sled measurements. A comparable percentage would have resulted in 18 such observations. Given the binning, a diver overestimation of large conch length by 1 cm would be sufficient to cause this discrepancy. However, a study comparing accuracy of scuba divers and stereo-video (Harvey et al. 2002) for fish length estimation showed high accuracy in length measured by scuba divers, but precision of length estimates was described as poor based on their standard deviations. Thus, reduced precision could also trigger some measures to fall into the next largest size class. No such difference was observed in the smallest length class where variance would be more constrained, with the divers and sled recording 1.3% and 1.0% of the sample, respectively.

Conch densities (conch ha^{-1}) estimated in this study were greater than in previous surveys (Table 3) at the same location in Puerto Rico, excluding a site in the 2013 survey that found an unusually high density (3090 conch ha^{-1}) of juveniles <10 cm (Baker et al. 2016). Mean total density was 14.1 conch ha^{-1} in 2013 (Baker et al. 2016), whereas estimates made by this study were 88.6 conch ha^{-1} for the diver survey and

Table 3. Queen conch density estimated by surveys in Puerto Rico from 1997 to 2016.

Source	Survey year	Location	Method	Density (conch ha^{-1})
This study	2016	Puerto Rico (SW shelf)	Sled	207.8
This study	2016	Puerto Rico (SW shelf)	Scuba transect	88.6
Mateo et al. 1998	1997	Puerto Rico (SW shelf)	Scuba transect	8.5
Baker et al. 2016	2013	Puerto Rico (SW shelf)	Scuba transect	14.0

210.5 conch ha^{-1} for the camera sled. Diver-based estimates were six times greater than the mean density reported by Baker et al. (2016), and sled-based estimates were an order of magnitude greater. However, this study concentrated surveys over a restricted set of habitats, which included prime conch habitat (seagrasses and algae); Baker et al. (2016) stratified their survey over several different habitat types but found highest densities among seagrass. Thus, some of the observed differences in conch density between studies may be because the present study selected habitats to ensure that conch would be observed to allow for comparisons between divers and the camera sled while at the same time avoiding potential damage to hard substrate/sled. This is unlikely to account for the full magnitude of observed density differences, however, especially given that even lower density estimates were made in previous dive surveys at this site (8.5 conch ha^{-1}; Mateo et al. 1998). A more relevant comparison is to the average density (16.9 conch ha^{-1}) observed by Baker et al. (2016) across their 11 sites that fell within the present study area. This estimate is only 20% greater, further supporting that the large differences observed between studies are not due to habitat effects.

Our results suggest that the population density of queen conch in southwestern Puerto Rico has increased in comparison with previous studies. In the survey conducted by Baker et al. (2016), juveniles in the length interval of 0–5 cm comprised 8.2% of total conchs observed, whereas in the present study, juveniles comprised a total of 1.27% with divers and <1% with the camera sled. Juveniles and newly mature adult conch were the most abundant age classes observed in this survey by both techniques which may be indicative of an increase or pulse in recruitment, though these conch may have not yet reached sexual maturity (Fig. 5). Indeed, if the conch in the station excluded by Baker et al. (2016) were included, the resulting density would have been 80.9 conch ha^{-1}, comparable to what was found here using the diver method, and these conch would now be adults. This is reflected in the new survey's results. The camera sled density estimate of adult conch and older ages (adults, old adults, and very old adults) was 66.12 conch ha^{-1}, indicating an increase of spawning queen conch from 4.1 conch ha^{-1} in 2013 (Baker et al. 2016), which could represent an increase in the reproductive capacity in this area. In contrast, the diver survey estimated a density 30.52 conch ha^{-1} for this age group which, while a substantial increase, was below the threshold of 50 conch ha^{-1} defined by Stoner and Ray-Culp (2000) for maintaining reproductive success (Stoner et al. 2019).

There are tradeoffs when considering which methodology to employ in future surveys. The camera sled can provide unlimited bottom time (Spencer et al. 2005), creates a permanent record, provides more accurate size estimations, and has a higher selectivity for smaller conch, which has management benefits. On the other hand, survey area for the camera sled is constrained by limiting use to sand/seagrass habitats, and image annotation requires specialized training and can be extremely time consuming. In particular, it was difficult to identify live vs dead conch and adult age classes in the sled images given that these are directly from above; substantial practice was necessary to detect the subtle differences and calibrate estimates across observers. In contrast, because divers view conch at an angle, where the shell lip thickness and live tissue can be visible, they could more easily distinguish live from dead conch and classify adult age classes. Nevertheless, no differences were observed among methods in the frequencies within adult age classes, suggesting that sufficient training can overcome these difficulties. Importantly, diver surveys do not require any post-survey annotation, which saves time in data processing and results in density estimates being more rapidly available. Image annotation is both time-consuming and laborious work. The use of towed camera systems is particularly advantageous for assessing conch in deep water areas, where rebreathers and or mixed-gas diving would otherwise be required (Garcia-Sais et al. 2012). With conch stocks now documented to occur down to at least 60 m (Appeldoorn, University of Puerto Rico, unpubl data), the question of the contribution of these deep stocks to potential recruitment remains open.

We suggest modifications in the methodology to improve the queen conch survey. For diver surveys, direct measurement with calipers (e.g., Doerr and Hill 2018), would result in precise shell length and lip-thickness data to have a more accurate size/age class identification. Stopping to measure all conch would, however, require fixed transect lengths, so that transect length (when a function of bottom time) is independent of conch density. Discontinued use of DPVs, or using narrower transects would also improve the detection of juveniles. This would reduce some of the gear selectivity differences, especially for juvenile conch. Reducing this size selectivity would broaden the density and size distribution estimates for the fishery independent surveys. Camera sled habitat selectivity can be reduced across all habitats and depths by using a flying array camera sled instead of a towed camera sled (e.g., Boman et al. 2016). Overall, the results of this study could improve the estimates of queen conch density across the Caribbean, particularly for surveys using DPVs or towed divers, where small individuals are more likely to be missed.

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