Developing a population assessment for Caribbean spiny lobster *Panulirus argus* in the United States Virgin Islands: lessons learned

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SEDAR91-RD-06

November 2024

Bull Mar Sci. 100(2):155–162. 2024
https://doi.org/10.5343/bms.2023.0014

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Advances in Ecosystem-Scale Coral Reef Visual Surveys

Guest Editors:
Laura Jay W Grove, Steven G Smith, Brian K Walker

Handling Editor:
Laura Jay W Grove

Date Submitted: 31 January, 2023.
Date Accepted: 18 March, 2024.
Available Online: 19 March, 2024.

ABSTRACT.—The Caribbean spiny lobster (*Panulirus argus*) is one of the most important fisheries in the US Virgin Islands. Low densities and life-history characteristics of lobsters have made reliable surveys in the region notoriously difficult, contributing to sparse and inconsistent fisheries-independent datasets to inform management decisions. Many existing and historical surveys are limited in their temporal and spatial coverage. In 2019, the National Park Service initiated a long-term monitoring effort of spiny lobsters in Buck Island Reef National Monument and Salt River National Historical Park and Ecological Preserve, St. Croix, US Virgin Islands, and Virgin Islands National Park, St. John, US Virgin Islands. Initial surveys show both density (3.06–7.07 lobsters ha^{-1}) and occupancy (0.11–0.12 sites with lobster) are low and not significantly different between the three parks. While survey efforts are currently focused on national parks, the 50 × 50 m gridded sample frame and stratification scheme are adaptable to the wider US Caribbean region, modelled after the multi-agency design to monitor reef fish with the National Coral Reef Monitoring Program. With the same survey footprint as reef fish surveys, the two methods could conceivably be co-located in the future, improving cost-efficiency and overall data quality. If expanded, this methodology could provide regional fishery managers with much needed density indices, though future surveys would benefit from a greater sample size or by supplementing with other methods that increase the number of observed lobsters to allow for robust size-frequency analyses.

The Caribbean spiny lobster (*Panulirus argus*) is a common decapod crustacean found throughout the tropical and subtropical western Atlantic (Williams 1965). *Panulirus argus* is an important resource harvested for local consumption and as an export fishery (Ehrhardt 2005). In the US Virgin Islands, the fishery grew considerably in the past 30 years and became one of the territory's most valuable commercial fisheries (Olsen et al. 2018). A recent stock assessment documented the need for long-term fisheries-independent studies specifically designed for *P. argus* to establish abundance indices, highlighting that available datasets were inconsistent in methodology, had limited temporal-spatial scales, or low overall sample sizes (SEDAR 2019).

Several factors make accurate fisheries-independent surveys of spiny lobsters notoriously difficult. The gregarious nature of *P. argus* can lead to samples with multiple or no individuals present (Herrnkind et al. 1975, Marx and Herrnkind 1986, Herrnkind and Lipcius 1989). Additionally, adult spiny lobsters seek shelter in complex hardbottom habitat during daylight hours, yet are mobile and actively forage at night, often in nearby seagrass habitats—presenting challenges in detectability (Herrnkind et al. 1975, Herrnkind 1980, Herrnkind and Lipcius 1989). Variability in habitat utilization throughout their life cycle and seasonal migrations to deeper water to reproduce require consistency in timing of surveys (Crawford 1921, Kanciruk and Herrnkind 1976, Herrnkind 1980, Marx and Herrnkind 1986). Low population densities further complicate sampling, requiring a high degree of replication or large survey footprints to reduce non-detections (Boulon et al. 1986, Boulon 1987, Wolff 1998, Beets et al. 1996, Mackenzie and Royle 2005). Altogether, developing an effective long-term lobster monitoring program has proven difficult. We present lessons learned from a baseline study in three US Virgin Islands parks to help inform potential strategies for monitoring spiny lobster across larger spatial and temporal scales in the region.

In 2019, the National Park Service (NPS) initiated a long-term monitoring study of *P. argus* within US Virgin Islands national parks: Virgin Islands National Park (NP) on St. John and Buck Island Reef National Monument (NM) and Salt River National Historical Park and Ecological Preserve (NHP&EP) on St. Croix (Richter et al. 2020). The monitoring protocol is designed to complement biennial reef fish sampling conducted in the territory as part of the National Oceanic and Atmospheric Administration's (NOAA) National Coral Reef Monitoring Program (NCRMP). The 50 × 50 m gridded sample frame, stratification scheme, and survey footprint are shared between the two monitoring efforts, providing a framework to extend these surveys into adjacent territorial waters.

Our objectives are to provide density, occurrence, and size information on the exploited-phase (≥89 mm) *P. argus* population in the parks to help inform management decisions. We prioritized park-wide density calculations, requiring randomized surveys of a known area. Expecting low population densities, we sought a survey footprint that was big enough to reduce non-detections, but small enough to be repeatable and allow for larger sample sizes while minimizing the likelihood of surveying beyond targeted strata. Previous studies of lobster in the region focused on catch-per-unit-effort from roving diver surveys (Cox et al. 2009; H Hicks, DPNR, pers comm), had very small survey areas (Pittman et al. 2008, Friedlander et al. 2013, NCCOS and SEFSC 2018, 2020, 2021), or targeted specific reefs (Cooper et al. 1975, Boulon et al. 1986, Boulon 1987, Tobias et al. 1988, Beets et al. 1996, Wolff 1998).

Fisheries-independent lobster research in the US Virgin Islands is lacking in recent years, though federal and territorial governments are showing renewed interest. NOAA partnered with NPS, the Department of Planning and Natural Resources (DPNR), and the University of the Virgin Islands in several projects to better examine the status of the lobster fishery in the US Virgin Islands. These projects include surveying deep (30–50 m) populations using the same methods as

Richter et al. (2020), as well as trap surveys and port sampling to evaluate life history, reproduction, age and growth, size structure, catch rates, and disease (K McCarthy and S Smith, NOAA Fisheries, pers comm). As part of the Southeast Area Monitoring and Assessment Program (SEAMAP) Caribbean, DPNR conducts timed-search surveys in the territory, studying size distribution, ageing, and reproduction patterns (H Hicks, DPNR, pers comm). A future cohesive territory-wide effort involving all partners could provide better quality data and meet the needs of each organization.

Materials and Methods

We conducted surveys at Buck Island Reef NM and Salt River NHP&EP on St. Croix in 2019 and at Virgin Islands NP on St. John in 2021, as a baseline effort for long-term lobster monitoring using the procedures outlined in the Spiny Lobster Monitoring Protocol (Richter et al. 2020). The Protocol utilizes the same sample frame and habitat classification as reef fish monitoring in the region because both organisms exhibit heterogenous distributions influenced by physical and biological habitat attributes (Williams 1965, Williams 1991, Bryan et al. 2013, Bryan et al. 2016). Sample domains are constrained by management boundaries of each park and limited to hardbottom habitats shallower than 30 m that *P. argus* use for shelter during daytime hours (Herrnkind 1980, Herrnkind and Lipcius 1989). Surveys are scheduled as a single sampling pulse during the same time of year to limit the effects of movement and seasonal migration and to maintain consistency in reproductive observations.

The sample frame employs a stratified-random design using 50 × 50 m grid cells, where each cell is assigned to a stratum based on coverage of hardbottom habitats of varying complexity. Within each stratum, cells are randomly selected using a discrete uniform probability distribution, which assigns equal selection probability to each cell (Law 2007). We evenly allocated samples across strata, though future surveys will incorporate a more efficient allocation. Next, a boat navigates to the centroid of a grid cell and searches for hardbottom visually or using sonar; divers then enter the water without conscious decision about the position of the survey and establish two adjacent 15-m diameter circular plots on the first hardbottom encountered and exhaustively search for lobster.

Upon encountering a lobster, observers first estimate the carapace length before attempting capture to measure actual carapace length and record demographic information (sex, condition of spermatophore/eggs). Lobsters are released after the assessment. Divers conduct a benthic assessment for each plot, including habitat photos and visual assessments of habitat type, abiotic footprint, slope, and surface relief. These assessments determine in which habitat stratum the sample actually occurred.

The primary measurable objectives are to determine status and trends of relative density (e.g., lobsters per 353 m^2), occupancy, and average size of exploited-phase lobster. Descriptive metrics like sex ratio and proportion of females with eggs and/or spermatophore are secondarily tracked.

For the analyses, we assume the data collected at a site is representative of the whole primary unit in which it was collected. Stratum densities are calculated, then summed using a weighting factor based on stratum area to calculate a density index across the domain. To calculate 95% confidence intervals, we used a nonparametric bootstrap using 10,000 samples with replacement using the "boot" package (Canty and Ripley 2021, Davison and Hinkley 1997) in R (R Core Team 2020). Occupancy calculations are identical to density, except values of 1 or 0 indicate the presence or absence of lobster. Average size in the exploited phase was calculated by averaging the carapace lengths of all observed lobsters that were greater than or equal to the legal limit of 3.5 inches (89 mm). Visual estimates were used if lobsters evaded capture. Kruskal–Wallis and Mann–Whitney *U* tests determined whether significant differences existed in average size between parks. Lastly, we ran a simulation in R, pooling observations of exploited-phase lobsters in all three parks to estimate sampling effort required to achieve various coefficients of variation (CV) based on the current stratification scheme (Smith et al. 2011).

Results

A total of 76, 32, and 72 sites were sampled in the Buck Island Reef NM, Salt River NHP&EP, and Virgin Islands NP surveys respectively. Spiny lobsters were infrequently observed, leading to low density and occupancy estimates with no significant differences detected between parks (Table 1). Relative density plots are presented for Virgin Islands NP (Fig. 1A), Buck Island Reef NM (Fig. 1B), and Salt River NHP&EP (Fig. 1C). The average size (SE) of exploited-phase lobster was significantly larger in Virgin Islands NP [125.4 (4.7) mm] than in either Buck Island Reef NM [108.6 (4.6) mm, $P < 0.01$] or Salt River NHP&EP [108.6 (3.2) mm, $P < 0.05$]. Figure 2 provides estimated sampling effort to achieve various CV targets based on pooled densities of exploited-phase lobsters in all three parks.

Table 1. Descriptive metrics for observed *Panulirus argus* in surveys conducted in Buck Island Reef National Monument (Buck Island Reef NM) and Salt River National Historical Park and Ecological Preserve (Salt River NHP&EP) in 2019 and in Virgin Islands National Park (Virgin Islands NP) in 2021. Individuals were only included in sex ratios and percentages of females with eggs or spermatophore when physical characteristics were clearly visible. Relative density (lobster ha^{-1}) and occupancy (sites occupied) for all observed and exploited-phase *P. argus* are also reported.

Park	Buck Island Reef NM	Salt River NHP&EP	Virgin Islands NP
Total Sites	76	32	72
P. argus Observed	23	27	31
P. argus Captured	14	8	15
Exploited (≥89 mm) : Unexploited (<89 mm)	15 : 8	7 : 20	19 : 12
P. argus Density: lob ha^{-1} [95% CI]	5.66 [2.55, 9.62]	18.11 [6.51, 32.54]	8.21 [3.68, 14.15]
Exploited-Phase (≥89 mm) Density: lob ha^{-1} [95% CI]	3.96 [1.41, 7.07]	7.07 [3.40, 16.69]	5.09 [2.26, 8.49]
P. argus Occupancy: sites occupied [95% CI]	0.16 [0.07, 0.27]	0.23 [0.08, 0.40]	0.12 [0.06, 0.18]
Exploited-Phase (≥89 mm) Occupancy: sites occupied [95% CI]	0.12 [0.04, 0.21]	0.11 [0.01, 0.25]	0.11 [0.05, 0.17]
Average Size (SE) in Exploited-Phase	108.6 (4.6) mm	108.6 (3.2) mm	120.6 (4.7) mm
Max Carapace Length	160 mm	125 mm	180 mm
Min Carapace Length	48 mm	40 mm	15 mm
Sex Ratio (M : F)	3 : 12	6 : 3	7 : 10
Percentage of Females with Eggs	41.7%	33.3%	20.0%
Percentage of Females with Spermatophore	66.7%	0.0%	40.0%

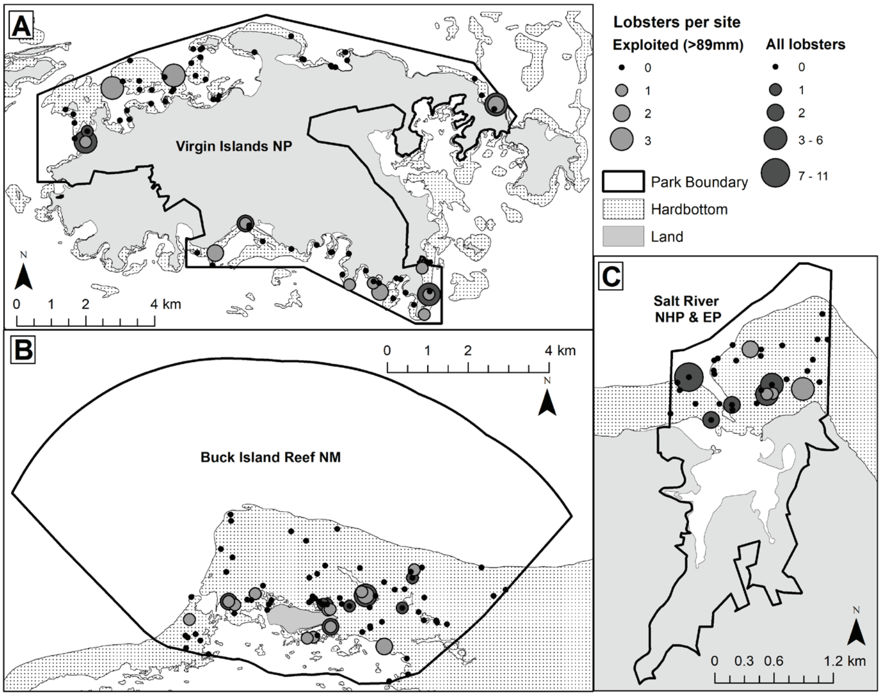

Figure 1. Relative density and distribution of exploited-phase *Panulirus argus* and benthic habitats in the US Virgin Islands: (A) Virgin Islands National Park, St. John; (B) Buck Island Reef National Monument, St. Croix; and (C) Salt River National Historical Park and Ecological Preserve, St. Croix.

Discussion

While baseline spiny lobster monitoring effort was intended for *P. argus* populations in three national parks in the US Virgin Islands, key features make it valuable for a fisheries-independent sampling effort at wider scales. Prioritizing density and occupancy as metrics rather than catch-per-unit-effort reduces bias, makes results comparable to other studies, and is more useful to managers. Modelling the sample design after the NCRMP reef fish surveys provides opportunities to expand efforts into adjacent territorial waters and affords the prospect of co-locating the surveys to increase sample size, cost-effectiveness, and assessment of spatial fisheries management (open vs closed areas).

Density and occupancy rates for lobster are low across the three national parks surveyed. A substantial concern when sampling low-density populations is the power to detect a significant change between sampling events if one exists. Gregarious species, like *P. argus*, exacerbate the issue by introducing a high degree of variance in density observations (e.g., 11 juveniles were observed at a single site in Salt River NHP&EP). Focusing on exploited-phase individuals, which aggregate somewhat less than juveniles, helps reduce the effect. Yet, if this methodology was used in a wider territorial effort, an estimated 152 samples achieve a CV of 20%, a common target in fisheries-independent assessments (Fig. 2). A percent change is statistically

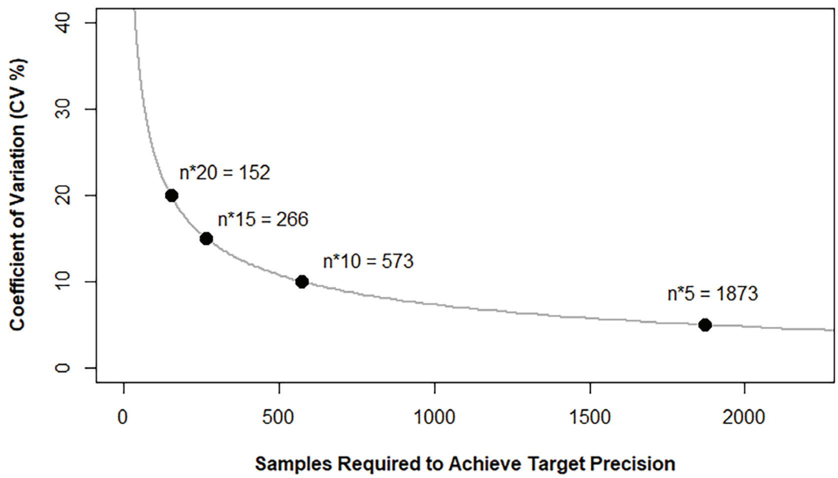

Figure 2. Sampling performance curve, pooling density observations of exploited-phase lobsters from the surveys in all three US Virgin Islands national parks (Virgin Islands National Park, Buck Island Reef National Monument, and Salt River National Historical Park and Ecological Preserve). The curve estimates the number of samples needed to achieve target coefficients of variation for a given geographic area with similar lobster densities and sampling strategy.

detectable at approximately twice the CV; thus the smaller the CV, the greater ability to detect changes in density (Smith et al. 2011).

Comparison of density metrics with historical studies is problematic, however a collaborative large-scale standardized approach using fixed-area plots could establish reliable density indices for the territory. The survey footprint of our study (353 m^2) is considerably larger and reduces the number of non-detections over the NCRMP lobster transects (30 m^2). The small area in NCRMP transects leads to high data sensitivity, where one additional lobster at a single site may double a density estimate for a park. Larger survey footprints reduce non-detections, but simultaneously decrease the possible number of overall sites if sampling effort remains consistent. We felt two 15-m diameter plots per site balanced being small enough for an exhaustive search ensuring high rates of detection probability, yet large enough to reduce non-detections over other methods. We also felt that maintaining consistency with the NCRMP reef fish surveys was important to allow for potential co-location of surveys.

One disadvantage of prioritizing density is that in low-density populations, the number of observed lobsters is low, which limits robust size-frequency analyses. While lobsters in Virgin Islands NP (n = 19) were significantly larger than those in Buck Island Reef NM (n = 15) or Salt River NHP&EP (n = 7), the low number of observed lobsters does not lend confidence to interpreting size-frequency data. Overall sample size should increase or be supplemented with roving-diver or trap surveys if robust size-frequency or demographic information is a priority.

With a lack of previous standardization of censusing techniques for spiny lobsters in the region, this study introduces a sampling scheme that is adaptable to include territorial waters outside parks. The survey methods and design model those that already sample reef fish in the region and could conceivably be coupled with those efforts to increase cost-effectiveness and provide much needed population level estimates for *P. argus* territory wide.

Acknowledgments

We thank B Arnette, M Chilcote, N Hanna Holloway, L Henderson, T Kelley, K Liburd, J Miller, C Pollock, C Pott, D Tyson, and R Waara for field assistance and Buck Island Reef NM and Virgin Islands NP for providing personnel, boats, logistics, and office space. This study was funded through the NPS South Florida/Caribbean Network, Inventory and Monitoring Division base budget.

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