Population assessments for 28 target coral-reef fishes of Guam based upon extensive fisheries-dependent and fisheries-independent data sources

Final Phase II Report

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Executive summary

Many studies have described negative trends in Guam's nearshore fish populations over the past two decades based upon: i) declining target species sizes and biomass in fisher landings, ii) regionally low, often lowest, observed fish biomass in Guam compared to other Pacific islands, and iii) catch success that is increasingly dependent upon favorable environmental conditions, such as access to windward reefs in the summer months. In response, marine protected areas (MPA) and limited gear restrictions associated with net fishing have become focal points of fisheries management that aim to provide broad protection for coral-reef fisheries. While studies have shown MPA policies have been effective in some instances, declines continued to be documented. Recently in 2020, the Guam legislature passed bill 53-35 to ban SCUBA-spearfishing which was a very contentious topic for over 30 years, despite its known threat to viable reef fish populations. Currently, there is a desire to build upon growing stakeholder engagement and begin a holistic approach towards managing Guam's fisheries resources into the future.

The first fisheries management planning (FMP) process was initiated last year by the Guam Division of Aquatic and Wildlife Resources (DAWR). In support of this evolving process, the present study conducted population assessments for 28 target species associated with the nearshore spear and bottom fisheries. These 28 species comprised the majority of landings over the past two decades. High resolution species assessments were conducted using a large suite of fisheries-dependent (FD, associated with landings) and fisheries independent (FI, associated with observations) data gathered from many contributing sources, institutions, and individuals. By assessing the potential status of each species from many different data sources, our study provided a novel consensus approach to evaluate species trends across space and time. In addition to these data sources, an extensive life-history database was synthesized and used to perform a common data-poor approach to evaluate each species called spawning potential ratio analysis or SPR.

Sufficient data existed to conduct population assessments for 26 out of 28 target species as the Napolean wrasse and bumphead parrotfish, *Cheilinus undulatus* and *Bolbometopon muricatum*, respectively, did not have sufficient data. For other species, an average of 10 (±3.8, SD-standard deviation) statistical tests were performed to assess trends across space, time, and fishing pressure gradients derived from 9 unique data sources. The evaluation process resulted in declining biomass or size trends for 15 of 26 (58%) species examined from FD datasets, and declining biomass or size trends for 15 of 24 (63%) species examined from FI datasets. Declining biomass and size trends were mainly found for large-bodied species within each family, and most clearly for parrotfishes, snappers, groupers, and emperorfishes. Conversely, non-significant or mixed trends were revealed for most small-bodied parrotfishes, surgeonfishes, rabbitfishes, rudderfishes, goatfishes, and small-bodied groupers and snappers. This disparity is largely reflective of life-history traits among species, whereby vulnerability increases with life-history strategies that decrease turnover times and yield larger individuals. Interestingly, among the 21 species with declining trends in either FD or FI data, 10 (48%) had declining trends attributed primarily to biomass *or* size, while 11 (52%) had declining trends of equal magnitude for biomass and size. Understanding both the current status of each species and the primary species response to fishing pressure provided valuable insight to guide potential management approaches.

SPR analyses were performed for 14 species that were selected as targets in the present study and also had locally-derived life-history data. In contrast to FI and FD data sources, SPR analyses

revealed that only 3 of 14 (21%) species had predicted SPR values below 0.3, or the suggested 30% management threshold. Further, many species associated with declining FI and FD trends had positive SPR results. In sum, the perceived status of target species from SPR analyses did not align well with the status reported by FI and FD data. However, SPR metrics describing potential management approaches for each target species often align well with the FI and FD recommendations. The SPR limitations were based upon the mathematical nature of the modelling coupled with differing biology associated with the diverse array of target species. Suspected causes were discussed, but ultimately, SPR appeared relevant for only a few species that meet the assumptions that underline the modelling process.

Potential management interventions should be designed to match the biology of each target species. Therefore, our outcomes were linked with two broad classes of management interventions, size-based or effort-based. Species with strong size-based responses to fishing pressure often represented "winners" that remained dominant in landings despite size shifts, discussed above. These species represent ideal candidates for size-based policies as one means of potential management (i.e, minimum, maximum, or slot-based). Meanwhile, species with strong biomass-based responses represent ideal candidates for management interventions that control overall fishing effort (gear-restrictions, marine protected areas, commercial-versus-subsistence fishing pressure, spawning seasons, and other similar approaches that address entire populations). Therefore, the results provided a guide for discussing the status and potential management of target species that will soon begin as part of the Guam fisheries management planning process that includes fishers, managers, scientists, and other sectors alike.

Introduction and background

While much research has been conducted on Guam's coastal fisheries over the years (Hensley and Sherwood 1993, Amesbury and Hunter-Anderson 2003, Gombos et al. 2007, Houk et al. 2012, Houk et al. 2018), there has been less work dedicated to conducting assessments of targeted fish species, actions that are ultimately needed to guide species-based management. In lieu of species-based policies, marine protected areas (MPA) have been the focus of coral-reef fisheries management efforts as these provide broad protection for coral reef fisheries within defined areas and potential spillover. MPA have proven successful in Guam, however, reports have revealed somewhat low MPA efficacies with MPA outer reefs typically holding ~1.5x more biomass compared to references sites, but MPA inner reef efficacies were increased to up to 3x for individual species (Taylor and McIlwain 2010, Williams et al. 2012, Houk et al. 2022, Taylor et al. 2022, Burdick 2023). Guam MPA were often reported as having similar biomass compared to the exposed eastern reefs that have limited accessibility due to seasonal trade winds in the winter months. Additionally, gear restrictions exist to prevent unwatched nets and regulate the mesh sizes of gill nets, yet the gill-net fishery is smaller in comparison to spear and bottom. Meanwhile, significant declines in Guam and greater Micronesia nearshore coral-reef fish populations have been reported by many studies despite the growth of MPA and instances of net regulations across the region (Martin et al. 2016, Weijerman et al. 2016, Cuetos-Bueno et al. 2018, Houk et al. 2018, Cuetos-Bueno et al. 2019). While enhanced enforcement efforts continue to improve MPA efficacy, MPA cover <20% of the coral-reef habitat on Guam and do little to address the remaining reef habitats. Alongside fishing pressure, two other primary stressors to Guam fisheries exist in the forms of land-based pollution (Houk et al. 2022) and climate change disturbances (Raymundo et al. 2019). Both appear to have secondary, negative impacts to fisheries habitats and resources. In sum, the limited nearshore habitat around Guam coupled with the large and growing human population and climate change continue to put a strain on fisheries resources.

In response to growing fisheries concerns, the political leadership of Guam has formed a stronger partnership with the natural resource management agencies. Evidence comes from the recently passed Public Law 35-78 on March 20, 2020, to ban SCUBA-spearfishing, a fishing method that has been a very contentious topic for over 30 years, despite its known threat to viable reef fish populations (Green 2003, Lindfield et al. 2014). While some species-based regulations exist for a few fish and invertebrates, there are no regulations regarding catch sizes or amounts for nearly all targeted coral-reef species. To address this concern, the Guam Division of Aquatic and Wildlife Resources (G-DAWR) requested support from the National Oceanic and Atmospheric Administration (NOAA) Pacific Islands Regional Office to develop a jurisdictional coral reef fisheries management plan for Guam to achieve sustainable fisheries.

Recent stock assessments have been conducted by the NOAA Pacific Islands Fisheries Science Center (PIFSC) for 12 target species using a data-limited approach that is based upon the estimation of spawning potential ratios (SPR) (Nadon 2019). These SPR approaches used both available and meta-analytically extrapolated life-history data combined with fisheries datasets from the NOAA PIFSC bio-sampling program and the G-DAWR creel program. Through these initial SPR modelling approaches, many challenges associated with data limitations surfaced that were due to varying assumptions and sources of life-history parameters and fish size distributions that both serve as critical inputs to SPR models. In assessing 12 species, Nadon (2019) found that four species had median SPR values below 30%, suggesting overfishing, with three other species near this limit. Ahrens & Nadon (2023) assessed seven species from Guam and highlighted at least two species with SPR < 0.3, a reference benchmark commonly used as a minimum target (Mace and Sissenwine 1993). Interestingly, Ahrens & Nadon (2023) demonstrated the wide variability that can occur when comparing assessment results based on locally-derived life-history parameters compared to meta-analytically imputed parameters, with the latter eliciting a higher likelihood of reflecting an overfished status due mainly to larger estimates of asymptotic lengths. In both studies, less than half of the species had locally-derived life-history information.

The present project built upon these initial findings and conducted holistic assessments of 28 target coral-reef fishes that accounted for over 70% of landings recorded on Guam since the 1980's. The objectives of this project were to gather a suite of fisheries-independent (FI) and fisheries-dependent (FD) datasets pertaining to Guam from local and federal government agencies, as well as key individuals associated with academic institutions such as the University of Guam Marine Laboratory (UOGML). Diverse data sources were first reviewed for statistical concerns and then used to conduct species assessments. Using data from many diverse sources provided a consensus approach to evaluate each species that incorporated multiple lines of evidence. We considered this akin to a population assessment or a population vulnerability assessment, within which several approaches were used to evaluate each species. In addition, extensive life-history data were synthesized from many studies and used to conduct SPR modelling to evaluate each species. The results provided novel insight in the strengths and weaknesses of each particular data source and SPR modelling. Most importantly, were discussed alongside each other to help Guam stakeholders make their own informed decisions during the ongoing FMP process.

Methods

The authors, in collaboration with G-DAWR, identified a suite of fisheries-dependent and fisheries-independent datasets that could contribute to population assessments for target coral-reef fisheries species. Sources of fisheries data were identified from published studies, grey literature including UOGML student theses and technical reports, and past and ongoing monitoring efforts by local and federal programs. The focal points for each data source were contacted and a request letter originating from the director of G-DAWR was provided alongside the request for data. Requests were granted for all but one identified data source, the NOAA PIFSC biosampling program that was not able to release data due to privacy concerns. Once acquired, data were examined for structure, format, and quality-control concerns that might limit their use. This included basic review and/or corrections to taxonomic nomenclature and database formats. Next, each dataset and species were examined for potential use by evaluating the species "presence" (95% confidence intervals surrounding mean values per unit replication > 0) and "resolution" (standard deviation ~ 0.5 mean or lower) (Table 1) (Houk and Taylor 2023). Cumulatively, this process resulted in (9) unique data sources with sufficient coverage around Guam and Micronesia to evaluate a suite of target species.

Target species

Dominant species that accounted for 70% of the biomass in fisheries-dependent datasets were determined. Subsequently, a final list of target species was selected by G-DAWR based upon: 1) dominance in landings, 2) local knowledge regarding historical exploitation (via fisher surveys), 3) G-DAWR needs pertaining to existing fisheries policies, and 4) a desire to include representative species across both freedive spearfishing and bottom fishing sectors that are most dominant (Table 1). Target species included two iconic large-bodied species known to be sensitive to exploitation, bumphead parrotfish and Napoleon wrasse, as well as several snappers, emperorfishes, parrotfishes, groupers, surgeonfishes, rabbitfishes, one rudderfish, and one trevally (Table 1).

Data sources and analyses

Each data source was unique to some extent and examined to describe how target species may be responding to fishing pressure. Depending upon the dataset, examinations included: 1) quantifying temporal trends in biomass, proportional biomass, and/or size structures, or 2) quantifying spatial trends of biomass, proportional biomass, and/or size structures across MPA status and geographic, east-west gradients of wave exposure known to be associated with fishing pressure. The outcomes and their statistical effect sizes provided a means to evaluate the exploitation status of each target species from many data sources. Additionally, the outcomes provided comparative results for each statistical test performed to evaluate the relative significance across all target species, and guide species outcome assessments.

Temporal trends were investigated using both linear and polynomial regressions that indicated decline, recovery, or no significant trends for each species, further defined in a previous study (Houk et al. 2018). Linear trends indicated a steady decline/improvement through time while polynomial trends indicated a rapid increase/decrease followed by stasis. Temporal trend data were aggregated annually and time-series regressions were performed using R base packages (R Development Core Team 2010). Because the DAWR time-series creel data represented a long-term trend (1990 to 2020), 3-year rolling averages were used to filter out random fluctuations and increase the signal-to-noise ratio associated with temporal trends. The best-fit regression models were evaluated based upon their effect sizes (R^2) and significance (P-values) while ensuring normality of residuals and lowest Akaike Information Criterion (AIC) scores.

Spatial trends, or limited temporal trends across 2-3 timeframes only, were investigated using pairwise testing for each species across MPA status, geography, and/or discrete time period (eastern wave-exposed reefs versus western protected reefs). Mean species biomass and sizes were first aggregated across replicate sites. Biomass data were log-transformed to improve normality when appropriate, while size data were not transformed. Comparative models were assessed for their effect sizes (t-values) and significance (P-values) while ensuring normality of residuals. For two datasets, insufficient species-based data existed for the majority of target species (NOAA National Coral-Reef Monitoring Program and the Guam Long-Term Monitoring Program). In these instances, binomial models indicating presence or absence were used instead of linear models.

G-DAWR creel

G-DAWR established a fisheries-dependent monitoring program in 1982 that targeted both commercial and recreational fishers. G-DAWR staff intercept fishers as they return from both boat-based and shore-based trips. Creel surveys followed a regular schedule, including shifts on weekdays, weekends, and evenings when peak fishing periods were noted for each of the fishery sectors (Figure 1). During each survey event, all fish were identified and measured to the nearest millimeter (mm) fork length, and a series of standard questions were asked to determine fishing location(s) and method(s).

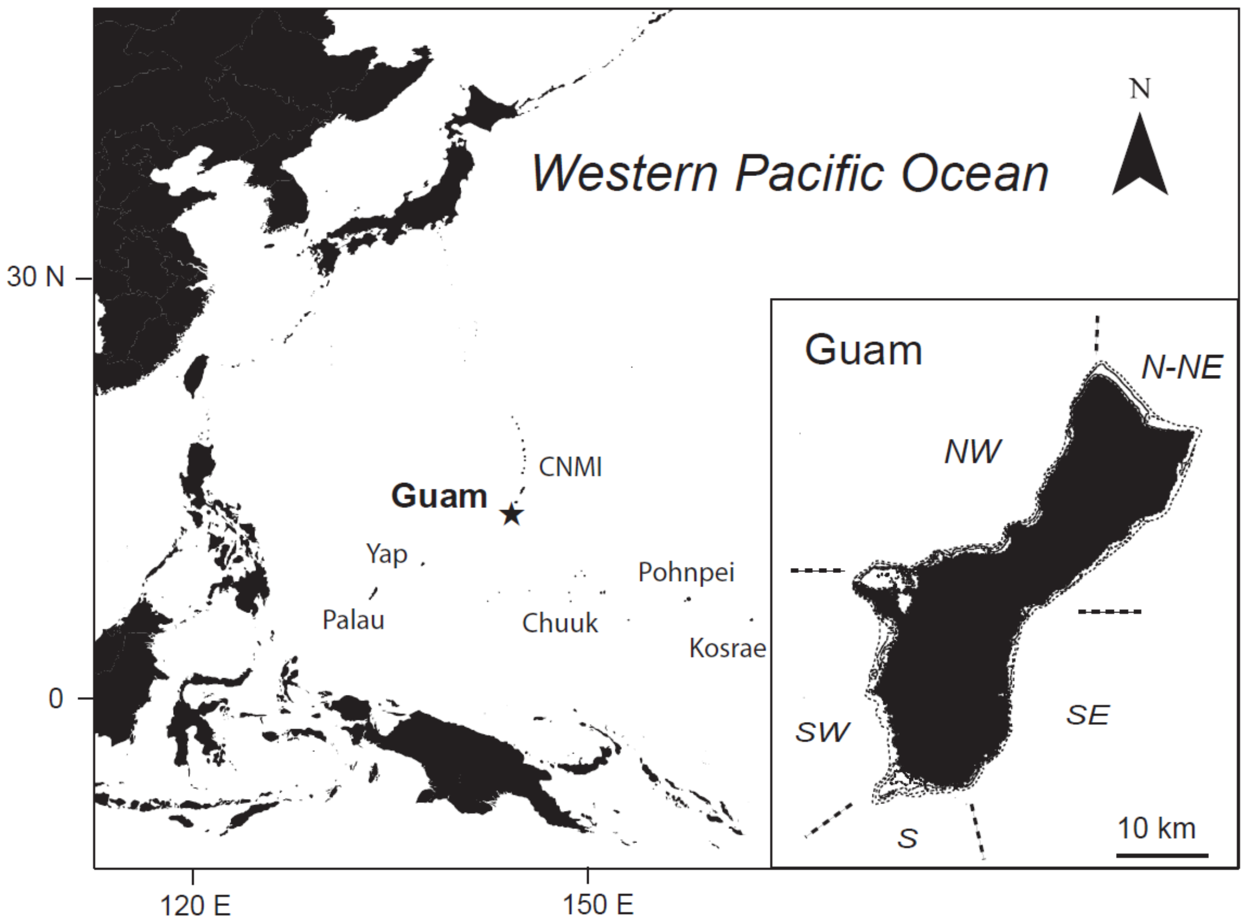


Figure 1. Map of the western Pacific Ocean highlighting the Micronesia islands where fisheries data collection programs exist. While the present study focused on Guam's nearshore fishery, several analyses examined species abundances and size structures across the Micronesia human population gradient as one means to depict species trends. The inset map of Guam shows the limited nearshore reef habitat (outline), and is divided into major sectors used for the creel data collection program (1980's to present).

Species	Micronesia FD (43)	Micronesia FI (44)	Guam LTMP-Resilience (10)	Guam LTMP (12)	G-DAWR Creel (65)	G-DAWR Bank Fishing (9)	Guam Ridge-to-Reef (24)	NOAA NCRMP (8)	Guam Stereovideo (36)	Life History	Total
Acanthurus lineatus	x	x			x		x	x		L	5
Aprion virescens					x	x				O	2
Bolbometopon muricatum	x	x								R	2
Caranx melampygus	x	x			x		x	x	x	L	6
Cephalopholis argus	x				x				x	O	3
Cheilinus undulatus	x	x								L	2
Chlorurus frontalis	x	x			x				x	L	4
Chlorurus microrhinos	x	x		x	x		x		x	L	6
Chlorurus spilurus		x	x	x	x		x	x	x	L	7
Epinephelus fasciatus					x	x			x		3
Epinephelus merra					x						1
Hipposcarus longiceps	x	x		x	x			?	x	L	5
Kyphosus cinerascens	x	x			x		x		x		5
Lethrinus olivaceus	x				x					O	2
Lethrinus rubrioperculatus	x				x	x				L	3
Lethrinus xanthochilus	x	x		x	x					O	4
Lutjanus fulvus		x			x			x	x		4
Lutjanus gibbus	x	x			x	x			x	O	5
Monotaxis grandoculis	x	x		x			x		x		5
Mulloidichthys flavolineatus					x					L	1
Naso lituratus	x	x	x	x	x		x	x	x	L	8
Naso unicornis	x	x			x		x			L	4
Scarus schlegeli		x	x	x	x		x	x	x	L	7
Siganus argenteus	x	x			x				x	L	4
Siganus punctatus	x				x					R	2
Variola louti	x				x	x			x	L	4
Scarus psittacus		x	x	x	x		x	x	x	L	7

Table 1. Target species identified by G-DAWR for formal analyses in the present study. The abundance or dominance of each species differed depending upon the data source and methods used to collect data (see methods). Species with mean values greater than their standard errors are noted with an "x" indicating that assessments for these species would likely be possible with adequate statistical power to detect trends should they exist. Number in (parentheses) after each data source indicate the number of reef-associated species for potential assessment. The last column, total, indicates the number of datasets available for each species. See methods for more information on these final target species selected for inclusion.

Species-based data were then entered into a standardized database that is available upon request to G-DAWR. While several sectors were covered by this program, SCUBA spearfishing (down to ~30 meter (m) depth), freedive spearfishing (down to ~18 m depth), gillnets, and shallow bottom fishing (down to ~90 m depth) were most common. The stream of data from this program differs slightly for each fishery, but reporting began in the late-1980s and continues today. Reporting for the SCUBA fishery diminished in the mid-2000s due to controversy among fishers, managers, and stakeholders, however, creel survey effort has remained consistent for other sectors (Weijerman et al. 2016, Houk et al. 2018). Most recently, SCUBA fishing has been banned on Guam by PL 35-78 on March 20, 2020. Species assessments using these data included temporal trends in size structure and proportional contribution to annual landings from the combined freedive spearfishing and bottom fishing datasets, representing the two disproportionally-dominant and legal forms of fishing. Data from 2020 were omitted due to COVID 19 when G-DAWR surveys were very limited.

G-DAWR bank fishing

G-DAWR conducted a series of bottom fishing survey trips to three remote banks that varied in distance from Guam in the fall of 1998 and spring of 1999 (n=5 trips total, Galvez Bank, White Tuna Bank, and Bank A, nearest to furthest, respectively). Each bank was visited during each trip that spanned a series of days (3 to 5 days). These surveys were conducted to evaluate the bottom fishing resources at three banks that differed in distance from Guam. Distance from Guam was considered akin to accessibility and therefore fishing pressure. In each instance, standardized fishing was conducted by bottom fishers placed in differing boat positions randomly. All fish landed were measured and weights recorded, along with other post-processing not relevant to the present report. Species-based analyses of biomass and size were conducted by first aggregating data to the bank-day, then examining across banks (i.e., across accessibility and exploitation gradient) following methods noted above.

Guam ridge-to-reef surveys

Coral, benthic, and fish assemblage data were collected on reefs adjacent 26 southern Guam watersheds during a 2020 to 2022 ridge-to-reef study. The goals were to investigate potential linkages between watersheds, fishing access, and the condition of ecological assemblages as measured from several key metrics of the coral, benthic, and fish assemblages (Houk et al. 2022). Fish data were used in the present study. Survey locations were similarly located at the southern edge of each channel associated with watershed discharge (Figure 2). Five, 50 m transects were laid along the 8–10 m reef slope contour and field protocols followed previous studies designed to address statistical power needs for site-level resolution (Houk and Van Woesik 2013, Houk et al. 2015). Food-fish assemblages were estimated from 12 stationary-point counts (SPC) conducted at ~20 m intervals along the transect lines. During each SPC, the trained observer recorded the species name and the size of all food-fish within a 5-6 m radius for a period of 3 minutes. Food-fish were defined as acanthurids, scarine labrids, serranids, siganids, carangids, labrids, lethrinids, lutjanids, balistids, kyphosids, mullids, holocentrids, and sharks. Fish fork lengths were converted to biomass using coefficients from regional fishery-dependent data when available (see below), or from FishBase when not available (www.fishbase.org). Species assessment using these data included examining spatial trends in both biomass and size-structure for target species across MPA and geography.

NOAA national coral-reef monitoring program

NOAA PIFSC Ecosystem Sciences Division conducts a national coral reef monitoring program for all Pacific Islands and territories associated with the United States. Sites are selected around each island across major habitat strata and three depth strata. Strata for Guam included geography (west versus east) and MPA status (Williams et al. 2012). In total, 30 to 100 sites were established proportionally across the defined strata in each of the three survey years (2011, 2014, and 2017), providing a consistent relative effort across each strata/year. All sites were surveyed using a modified SPC method. The SPC protocol involves a pair of divers conducting simultaneous counts in adjacent, visually estimated 15-m-diameter cylindrical plots extending from the substrate to the limits of vertical visibility. Prior to beginning each SPC, a 30-m line was laid across the substratum to assist divers conducting surveys. Each survey consisted of two components.

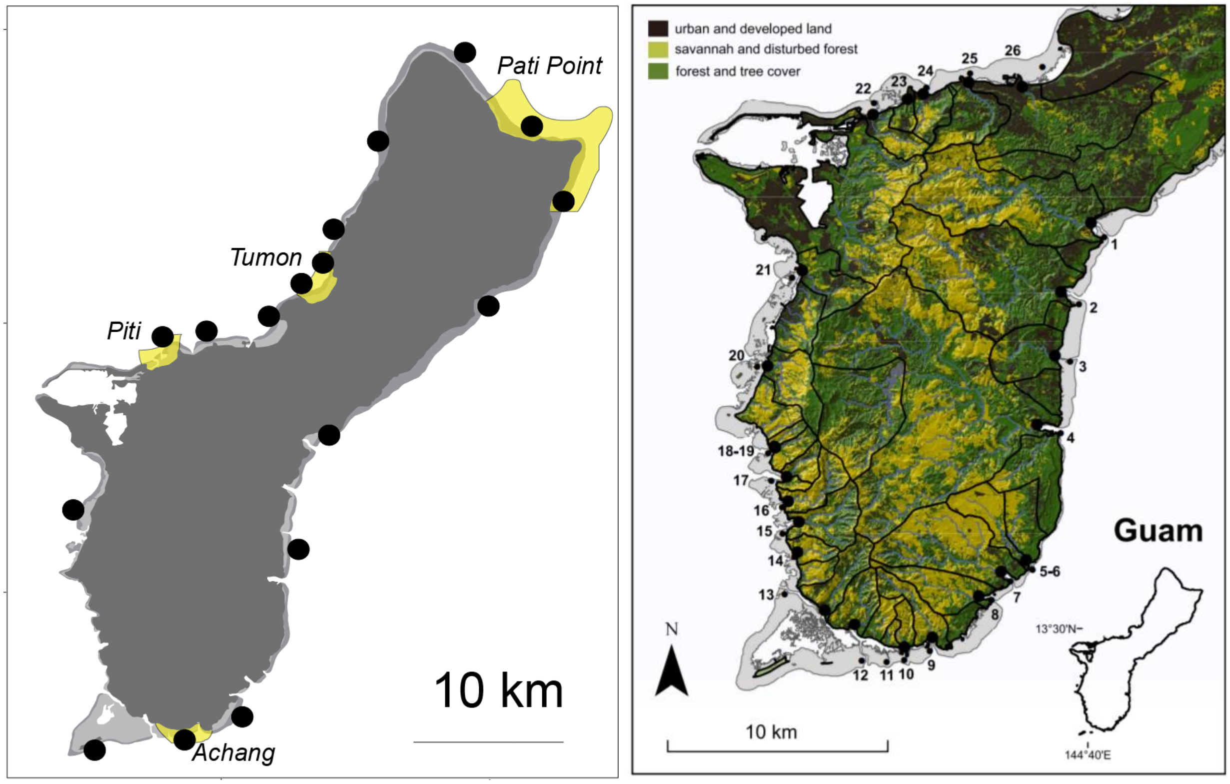


Figure 2. Representative maps of Guam associated with differing research projects and datasets that were used to evaluate target species. Sites associated with the stereo-video dataset are shown on the left while sites associated with the ridge-to-reef dataset on the right. Each dataset used in this study was associated with sites spread across geography, protection status, and/or time. These factors were used as a basis to assess target species.

The first of these was a 5-minute species enumeration period in which the diver recorded the taxa of all species observed within their cylinder. At the end of the 5-minute period, divers began the tallying portion of the count, in which they systematically worked through their species listing for each species and recorded the number of fish and size (total length, TL, to nearest centimeter (cm)) of each individual fish. The tallying portion was conducted as a series of rapid visual sweeps of the plot, with one species-grouping counted per sweep. To the extent possible, divers remained at the center of their cylinders throughout the count. In cases where a species was observed during the enumeration period but was not present in the cylinder during the tallying period, divers recorded their best estimates of size and number observed in the first encounter during the enumeration period and marked the data record as ‘non-instantaneous.’ The present study aggregated biomass and size data to the site level, then aggregated across the island to produce annual means for each target species. Data were analyzed across years using pairwise testing described above treating the limited number of years as discrete factors. This was the best approach to account for high variability and statistical uncertainty found within MPA or geographic strata, while considering sites were established around the island in similar proportion each year.

Guam long-term monitoring programs

The Guam long-term coral-reef monitoring program represents a complemental program to the national monitoring program conducted by NOAA-NCRMP. The key differences are survey designs as the survey protocols were identical (Burdick 2023). Survey designs were focused on examining MPA efficacy through time and therefore sampling only occurred in MPA as well as reference locations. During each survey year, between 20 to 35 sites were established in the MPA and reference locations. This program began in 2010 and currently includes survey data for Tumon (five years), Piti (three years), and Achang (two years). The continuously paired nature of this data for Tumon and Achang allowed for their aggregation across years, and pairwise testing for priority species as described above.

The Guam long-term monitoring program also conducted two snapshot resilience-based surveys associated with the 2015 to 2017 El Nino Southern Oscillation events. During each timeframe, 20 sites were selected for investigation around the island at a shallow (3m) and intermediate (8m) depth. Each site-survey included laying out 3 x 50 m transect lines and conducting (6) replicate SPC surveys for only herbivores and mobile predators. SPC protocols were similar to those above. This dataset allowed for both a geographical east versus west and MPA versus reference investigation following the above noted analytical methods.

Stereo-video surveys of Guam commercial fishes

This dataset was completed by the UOGML with Brett Taylor as the principal investigator. These data represent repeat surveys of reef fish assemblages on outer reef slopes of Guam during two time periods a decade apart (2011/2012 and 2021; at this time, only parrotfishes annotated for the 2021 survey period) to investigate the effect of fishing pressure, habitat variability, and the two time periods on fish composition, size structure, and ecological function such as grazing potential in parrotfishes (Taylor et al. 2015, Taylor et al. 2022). The surveys were conducted using diver-operated stereo video across 17 fixed sites around Guam using 24-minute (2011/12) or 30-minute (2021) timed swims at two depths (6-10 m and 18-20 m) with the distance measured by GPS using a surface buoy, covering an average area of 1.1 hectares per site. Individual fish within 8 m in front and 2.5 m on either side of the camera trajectory were identified to species level, annotated by color phase (for parrotfishes and humphead wrasse, as most of these species have initial and terminal phases broadly associated with sex), and measured to the nearest mm fork length. The 17 sites (Figure 2) span multiple MPAs as well as a wide range of environmental and anthropogenic factors (e.g., exposure, benthic substrate, fishing pressure, adjacent habitats) that are incorporated in the data set. The high amount of survey area at the site level facilitates detailed size structure analysis at the site level for the more common species (total size estimates exceed 15,000 observations). The above noted citations refer to past and present uses of this dataset to examine changes in parrotfish biomass, assemblage composition, and size structure associated with gradients of fishing pressure through space and time, and has been used to assess the influence of life-history traits on the intrinsic vulnerability of species to overexploitation.

Micronesia fisheries-dependent datasets

Fisheries-dependent datasets have been collected through many collaborative efforts over the past decade across Micronesia, including: Guam, Commonwealth of the Northern Mariana Islands (Saipan and Tinian islands), Yap, Pohnpei, Chuuk, Kosrae, the Republic of Palau, and the Republic of the Marshall Islands (Majuro and Arno atolls) (Figure 1). Fisheries-dependent datasets were derived from standardized, intensive efforts across one year in most cases, or across major seasons in one instance. These provided representative snapshots of the nearshore spear, net, and bottom fisheries. Daily visits to prominent fish markets, or visits to prominent fishers, were conducted where fishers were interviewed, and each fish landed was photographed on top of a measuring board. Fork lengths were generated from the photographs, and daily/seasonal trends were examined by coupling length data with fisher interviews to determine course-scale locations. These surveys provided between 30,000 and over 200,000 fish measurements per island-year depending upon the island size. Summaries of island-specific fishery trends and catch data have previously been published and proportional contribution and species skewness data were collected for present use (Houk et al. 2012, Houk et al. 2017, Cuetos-Bueno et al. 2018, Houk et al. 2018, Rhodes et al. 2018, Cuetos-Bueno et al. 2019). For Guam, comparative data originated from G-DAWR creel surveys from the past decade as well as size-data from a recently completed UOGML thesis noted below. The human population-reef-area for each Micronesia island was incorporated from the published studies, and regression models were examined to determine whether a species proportional biomass or size increased or decreased along the human population gradient. Regression modelling followed the protocols noted above. Because size-structures are known to shift with local oceanography and island geology, we generated skewness values associated with the size structure from each island as a comparable metric. Positive skewness values indicate a growing proportion of smaller fish.

Micronesia fishery-independent datasets

Fisheries-independent datasets have been collected over the past 10 years from many jurisdictions across Micronesia, including: Guam, Commonwealth of the Northern Mariana Islands (Saipan and Tinian islands), Yap, Pohnpei, Chuuk, Kosrae, the Republic of Palau, and the Republic of the Marshall Islands (Majuro and Arno atolls). Data were collected by many organizations and individuals in a collaborative partnership that defines the Micronesia coral-reef monitoring program (https://micronesiareefmonitoring.com/). Data from Guam were associated with the ridge-to-reef project noted above and also other ongoing efforts by the same principal investigators that have island-wide coverage and similar regional protocols. For each island, long-term monitoring site selections were stratified across (i) management regimes, (ii) wave exposure, (iii) islands, and (iv) major reef habitats, to be representative of each island (Houk et al. 2015), with the total number of sites proportional to the area of reef habitat. The sizes and abundances of target food-fishes were collected using standard visual census techniques by experienced and calibrated observers. Protocols were identical to those described above for the Guam ridge-to-reef dataset. Data analyses were identical to those described above in the Micronesia fisheries-dependent dataset.

Guam life-history database and spawning potential ratios

Information on the life histories of organisms represents the foundation to population dynamics. Life-history information has often been considered a limiting factor for resource managers in tropical coral reef environments worldwide. However, in recent years Guam and the broader

Micronesian region has emerged as valuable node for information on the life histories of harvested coral reef fish species. For example, Guam has more species with locally-derived life-history information compared to any other tropical island nation. The present report synthesized a dataset of life-history parameters for 46 species of commercially-harvested reef-associated fishes (Appendix 1). Among these, 80% of species have life-history data collected from Guam or nearby Saipan, Commonwealth of the Northern Mariana Islands, 11% are drawn from the broader Micronesian region, and 9% are from other regions in the Pacific such as American Samoa and Solomon Islands. Life-history data were generated from fish captured across all dominant fishing sectors, including night/day spearfishing, hook-and-line, surround nets, and throw nets. Best-fit parameters were provided for asymptotic length, growth coefficients, size at settlement, natural mortality, life span, length-weight coefficients, reproductive seasonality, size-and-age at maturity, reproductive contribution relative to body mass, whether or not species exhibit sexually dimorphic growth, and M/K ratios.

Parameters from the life-history dataset were combined with catch data and incorporated into population demographic models predicting yield-per recruit, spawner biomass per recruit, fishing mortality (F) relative to natural mortality (M), and finally, spawning potential ratios (SPR). The variability and dynamics of life-history parameters and catch data both have strong influences on the outcomes of SPR modeling. We outline several key concerns, discuss their relative influence on life-history parameters, and review our assumptions and decisions for selecting life-history parameters and species for SPR analyses in detail (Appendix 2). In compliment to using only locally-derived life-history data, we used length-based catch data from two sources: 1) DAWR creel data 2010 to present, freedive spearfishing and bottom fishing, and 2) a recently completed UOGML thesis project that intensively collected fish size-at-capture data during 2021 for the same sectors.

SPR analyses then followed several studies that previously defined the approach and developed an R package for use (Hordyk et al. 2015, Hordyk 2019, Nadon 2019, Ahrens and Nadon 2023). Given significant documentation that exists, a brief description is provided. Length-based SPR uses an iterative mathematical approach to evaluate several key metrics needed to eventually estimate SPR, one commonly used indicator of fisheries exploitation. SPR is rooted in several life-history parameters including L_{inf} or mean asymptotic length, L_{50} and L_{95} or size at which 50% and 95% of the population is estimated to be reproductively mature, M or natural mortality rate ($year^{-1}$), and K or growth coefficient ($year^{-1}$). These key parameters were introduced above and reviewed prior to use (Appendix 2). In compliment to life-history parameters, length-based vectors representing sizes-at-capture were used to determine the selectivity size, or SL_{50} and SL_{95}, 50% and 95% selectivity respectively. Finally, fishing mortality was estimated with knowledge of natural mortality (M), defined as the proportion of individuals expected in any given size class without fishing, and the proportion of individuals found in the catch. Fishing mortalities in each size class were then converted into spawning potential ratios based upon their relative proportion in the catch data coupled with the exponential relationship between length, weight, and gonad development. In sum, the SPR represented the ratio of spawning potential based upon the catch data divided by the spawning potential with fishing absent. The studies and R package noted above provide mathematical documentation to accompany this logical description. Notably, 30% SPR has been suggested as a benchmark to describe the overexploitation of species because at least

30% of spawning biomass is estimated to ensure sufficient recruitment for sustainable populations (Mace and Sissenwine 1993).

Results

Fisheries-dependent and fisheries-independent assessments

Sufficient data existed to conduct population assessments for 26 out of 28 target species from a suite of fisheries-dependent and fisheries-independent data sources (Table 1). The Napolean wrasse and bumphead parrotfish, *Cheilinus undulatus* and *Bolbometopon muricatum,* respectively, did not have sufficient data to make any assessments. For other species, an average of 10 (±3.8, SD-standard deviation) statistical tests were performed to assess trends across space, time, and fishing pressure gradients derived from 9 unique data sources (Tables 2-3, species outcomes for fisheries-dependent and fisheries-independent data, respectively). Results from fisheries-independent datasets examinations revealed declining biomass and size trends for 57 out of 175 (33%) of possible tests, increasing trends for 6% of tests, and non-significant trends for 61% of tests. Results from fisheries-dependent examinations revealed declining biomass and size trends for 42 out of 104 (40%) of possible tests, increasing trends for 17% of tests, and non-significant trends for 43% of tests.

The outcomes of species examinations were generalized into 6 categories based upon the relative effect sizes from statistical tests (see final column, Tables 2-3). Outcomes represented author reviews of the effect sizes that were compared across species for each statistical test, or within each column, but not compared across rows that represented different datasets and tests (Tables 2-3). The outcome categories depicted the primary species trends, positive, negative, or non-significant. For positive and negative trends, outcome categories also depicted whether size or biomass responses were most prevalent, or if both were equal. These outcome categories aimed to provide both species assessments and provide a framework to link species with potential management strategies that match their biology (discussion).

Summary graphs associated with individual datasets were prepared for six representative species to aid the interpretation of the species outcome tables, and to help interpret how outcome categories were assigned (Figures 3-8). These six species were selected to visualize diverse outcomes for large-and-small bodied species across different fisheries sectors. Representative species results included:

1) ***Chlorurus microrhinos*** – a large-bodied parrotfish with declining biomass trends across space and time as the primary response in both FD and FI datasets, and negative trends from 10 of 12 (83%) possible statistical tests.
2) ***Naso unicornis*** – a large-bodied surgeonfish with both negative and non-significant biomass and size trends from FD and FI data examined across space and time. Responses included declines from 6 of 14 (43%) possible tests, non-significant results from 50%, and increasing proportional biomass associated with 1 (7%) data source that examined fisheries-independent data across Micronesia.
3) ***Monotaxis grandoculis*** – a large-bodied emperorfish with non-significant trends dominant from FD datasets and declining size and biomass trends from FI datasets. Overall, non-significant trends existed from 9 of 13 (69%) possible tests, declining size

and biomass from 3 tests (23%), and increasing proportional biomass from 1 (7%) data source that examined fisheries-independent data across Micronesia.

4) ***Chlorurus spilurus*** – a small-bodied parrotfish with increasing biomass and size trends from FD datasets, but declining trends from FI datasets. Overall, declining biomass and size was found for 6 of 13 (46%) possible tests, non-significant results from 31% of tests, and increasing proportional biomass found in fish landings and observations across Micronesia's human population gradient (23%).
5) ***Variola louti*** – a large-bodied grouper with declining biomass trends across space and time as the primary response in both FD and FI datasets, and negative trends from 8 of 11 (73%) possible tests.
6) ***Lethrinus rubrioperculatus*** – a large-boded emperorfish with declining biomass trends across space and time as the primary response in both FD and FI datasets, and negative trends from 3 of 5 (60%) possible tests.

Cumulatively, this evaluation process resulted in declining biomass or size trends for 15 of 26 (58%) species examined from FD datasets, and declining biomass or size trends for 15 of 24 (63%) species examined from FI datasets. Declining biomass and size trends were mainly found for large-bodied species within each family, and most clearly for parrotfishes, snappers, groupers, and emperorfishes. Conversely, non-significant or mixed trends were revealed for most small-bodied parrotfishes, surgeonfishes, rabbitfishes, rudderfishes, goatfishes, and small-bodied groupers and snappers. This disparity is largely reflective of life-history traits among species (Appendix 1), whereby vulnerability increases with life-history strategies that decrease turnover times and yield larger individuals. This pattern was observed within some families (e.g., scarine labrids) and also broadly across families (e.g., snappers and emperors versus acanthurids and siganids). Interestingly, among the 21 species with declining trends in either FD or FI data, 10 (48%) had declining trends attributed primarily to biomass *or* size, while 11 (52%) had declining trends of equal magnitude for biomass and size. Understanding both the current status of each species and the primary species response to fishing pressure provided valuable insight to guide potential management approaches (*discussion*).

We last report some disparities between FI and FD data sources. While a similar proportion of species were found to have declining size or biomass responses from both FI and FD data, the outcomes of individual species assessments differed for 46% of species depending on whether FI or FD data were examined. These results were unsurprising considering that certain species had a greater or lower presence within FI versus FD datasets. For example, many target bottomfish had reduced presence or even absence in FI datasets but were better captured by FD analyses. Thus, interpretations of the present results can be aided by understanding species biology, fishing techniques used to capture each species, and the methodological details associated with each data source.

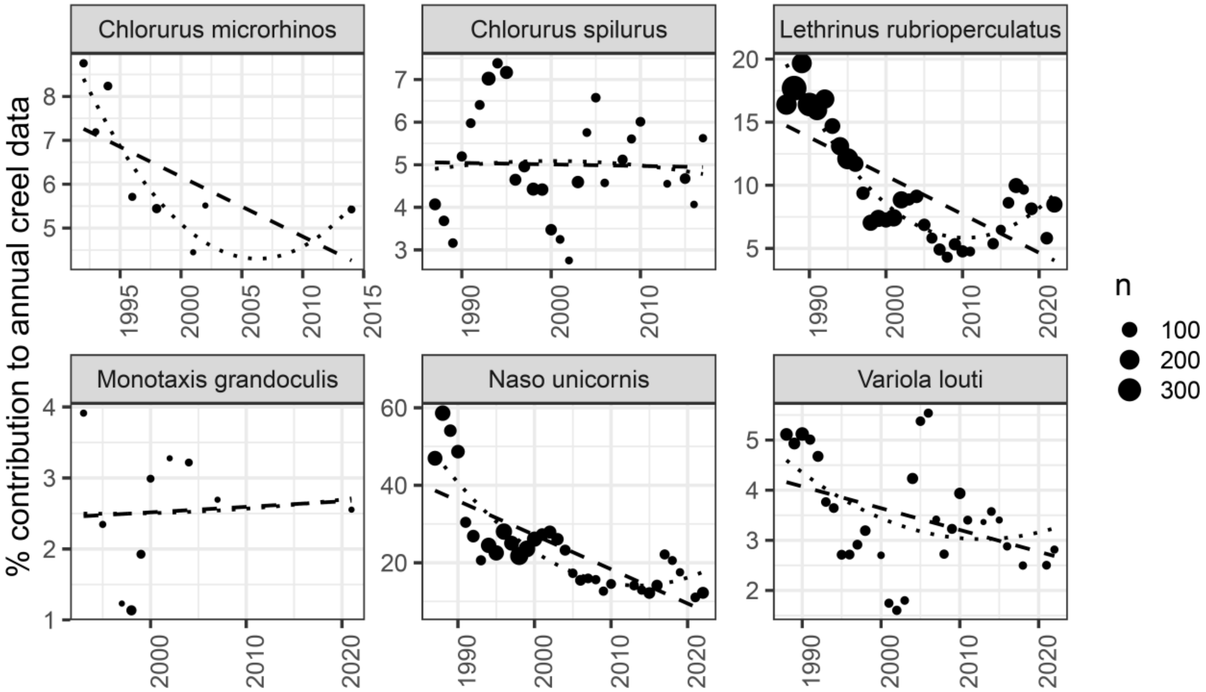


Figure 3. DAWR creel data trends in proportional biomass through time. Results for six representative species associated with the freedive spearfishing and bottomfishing sectors are shown, however, analyses were conducted for all species with sufficient data. Dashed lines indicate linear fits through the data points while dotted lines represent second order polynomial fits. Lines serve to visualize potential trends that were formally investigated for each species with statistical tests (Tables 2-3). Circle sizes indicate number of fish measured by the creel program in each year.

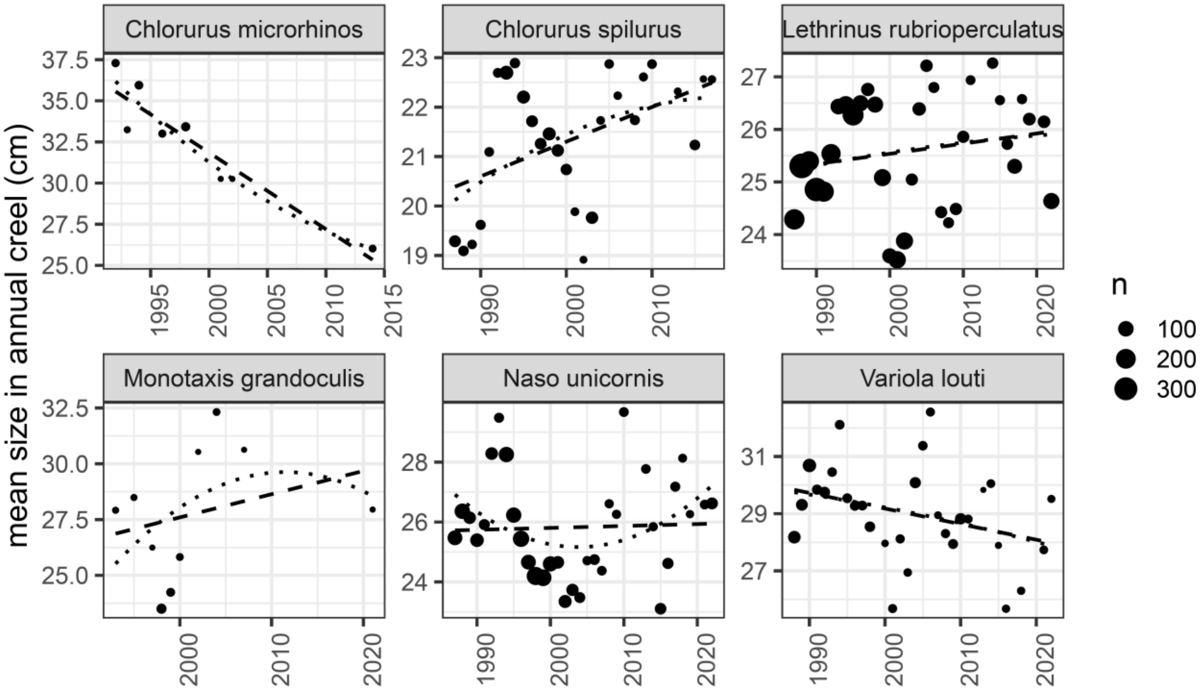


Figure 4. DAWR creel data trends in size structure through time. Results for six representative species associated with the freedive spearfishing and bottomfishing sectors are shown, however, analyses were conducted for all species with sufficient data. Dashed lines indicate linear fits through the data points while dotted lines represent second order polynomial fits. Lines serve to visualize potential trends that were formally investigated for each species with statistical tests (Tables 2-3). Circle sizes indicate number of fish measured by the creel program in each year.

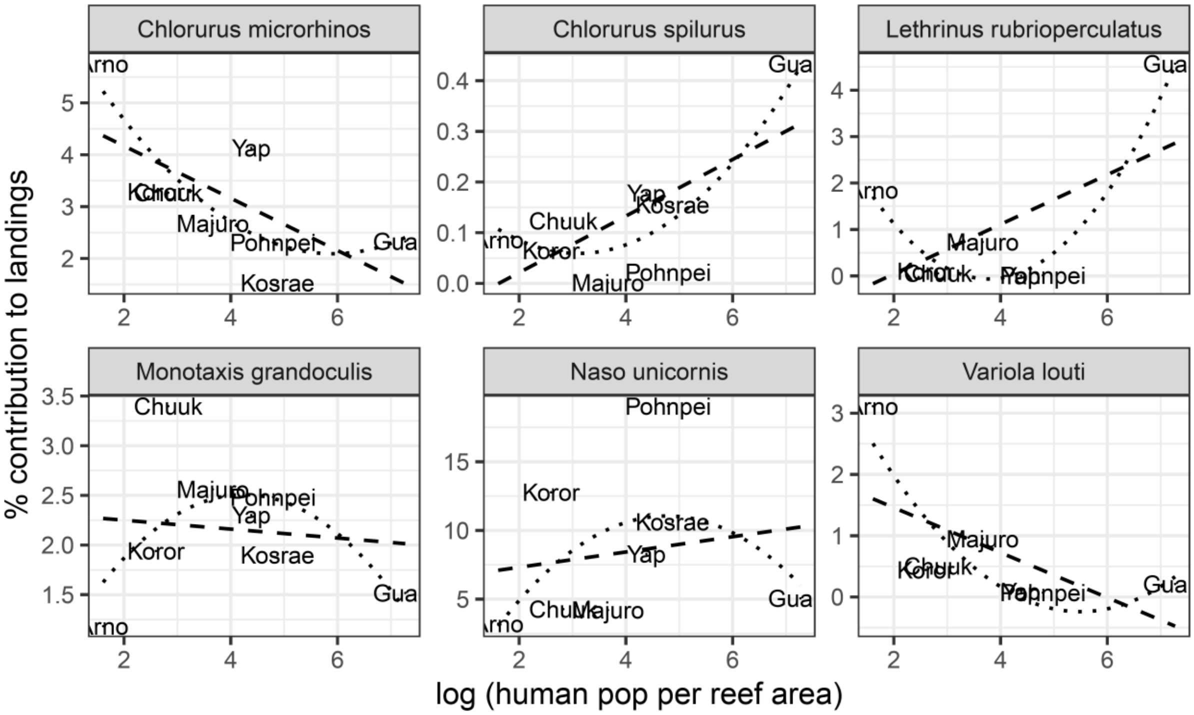


Figure 5. Proportional contributions to landings for six representative species associated with standardized fisheries-dependent studies across several Micronesia islands. For all islands, data originated from freedive spearfishing and bottom fishing sectors were most dominant and used for consistency (methods and citations). Dashed lines indicate linear fits through the data points while dotted lines represent second order polynomial fits. Lines serve to visualize potential trends that were formally investigated for each species with statistical tests (Tables 2-3).

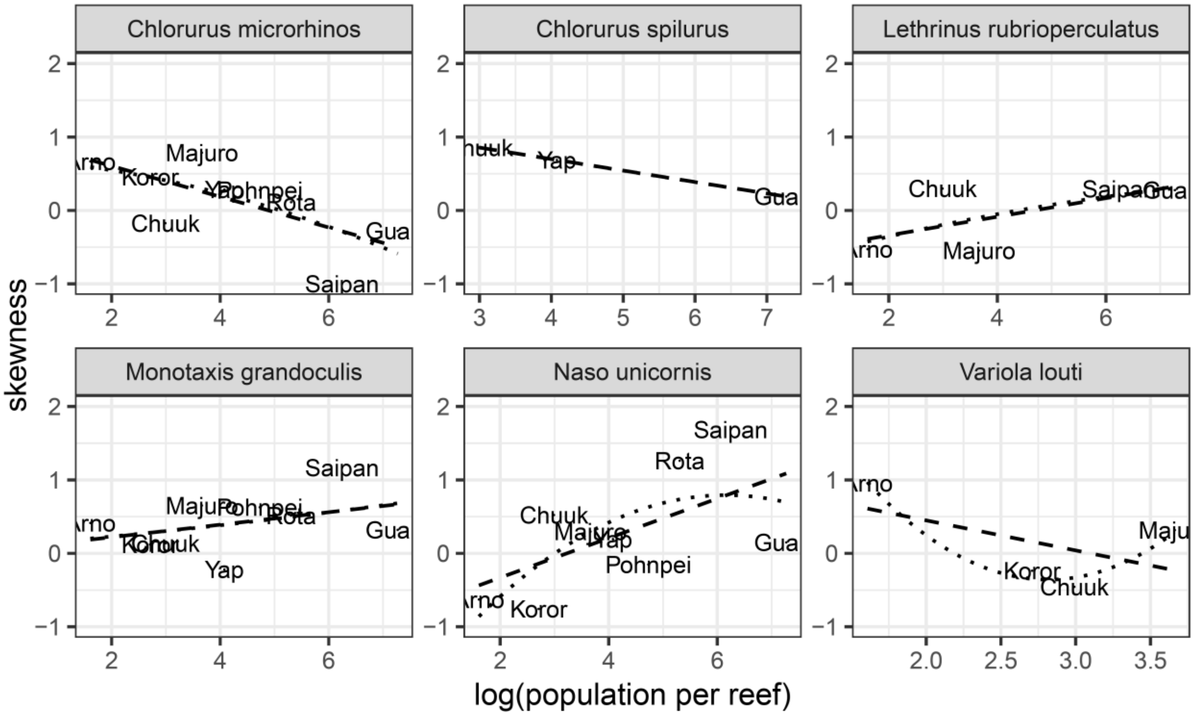


Figure 6. Skewness of size structures for six representative species associated with standardized fisheries-dependent studies across several Micronesia islands. Positive skewness indicated size structures that have a greater proportion of smaller fish and few larger fish. For all islands, data originated from freedive spearfishing and bottom fishing sectors were most dominant and used for consistency (methods and citations). Dashed lines indicate linear fits through the data points while dotted lines represent second order polynomial fits. Lines serve to visualize potential trends that were formally investigated for each species with statistical tests (Tables 2-3).

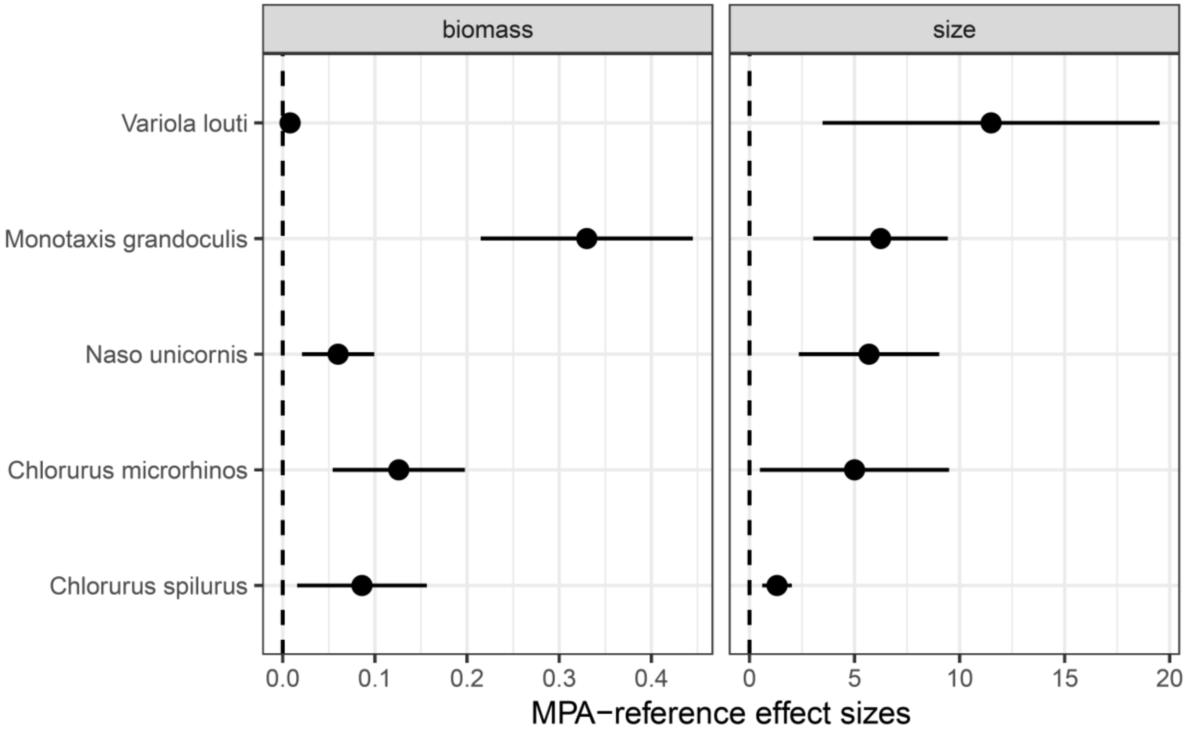


Figure 7. Assessments for five representative species with sufficient data in the Guam ridge-to-reef fisheries-independent surveys. Effect sizes with standard error bars indicate the relative increases in biomass or size inside of MPA compared to reference sites. Generally, error bars that did not overlap with the dashed line (0) represent statistical significance, however, statistical tests were conducted for all species with sufficient data (Table 3).

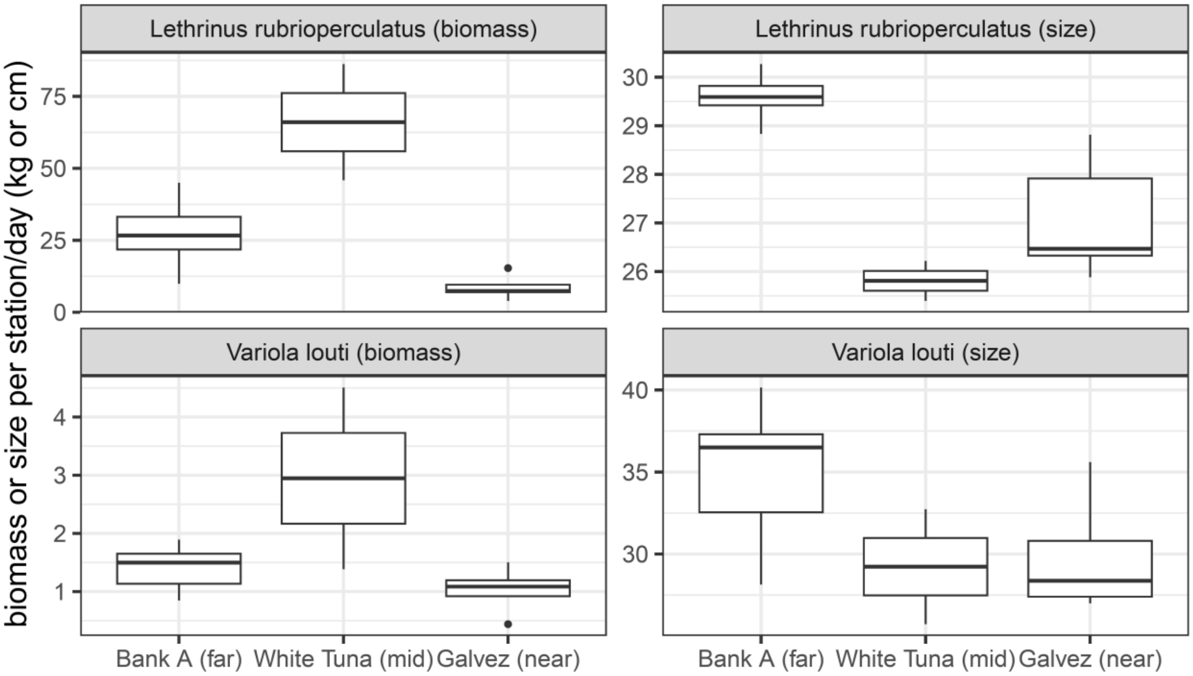
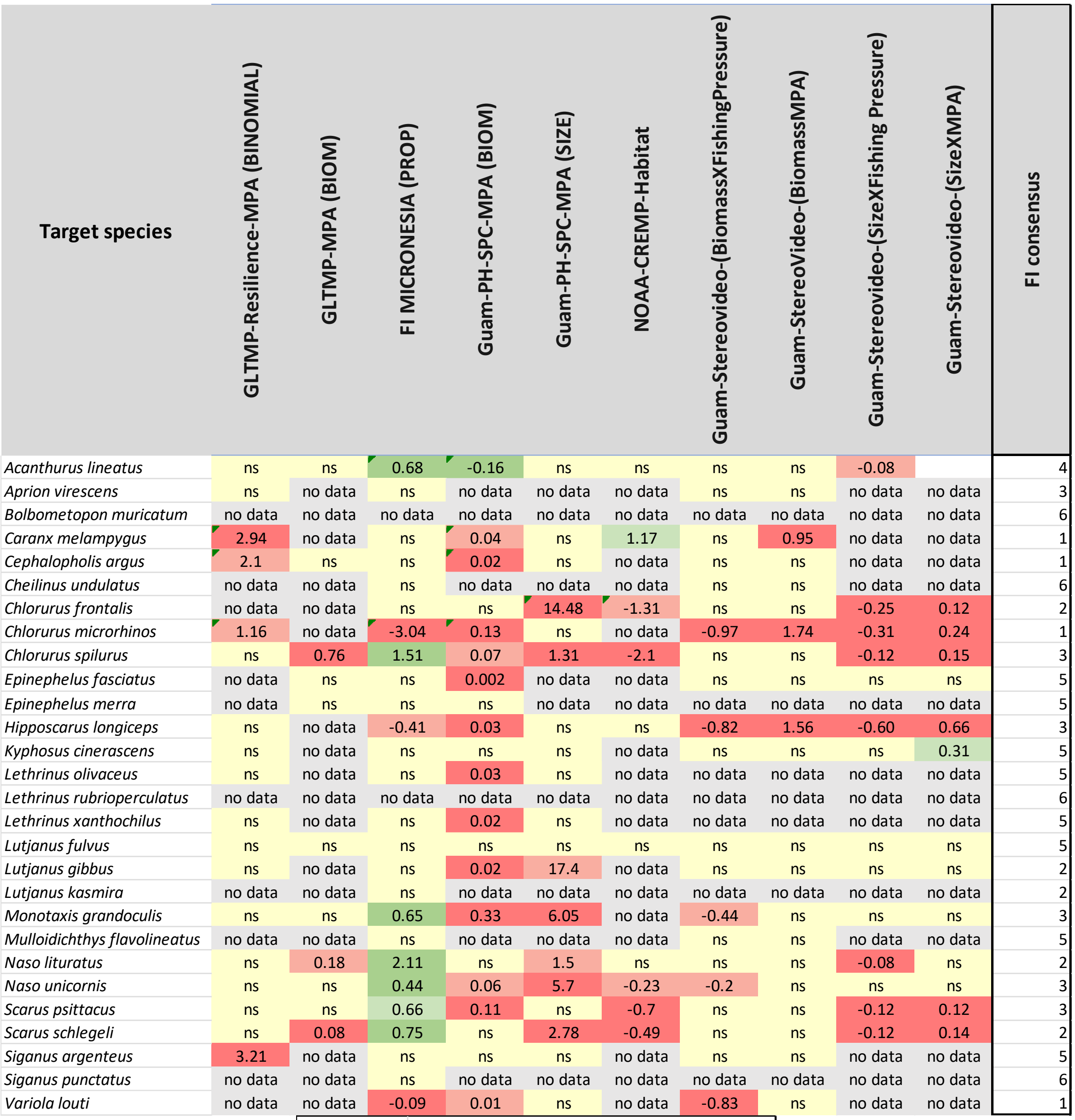


Figure 8. Assessments for two representative species with sufficient data in the DAWR bank fishing dataset. Bottomfishing landings were compared between three banks at varying distances from Guam for each species with sufficient data (far, mid, and near) (Table 2).

Target species	**FD MICRONESIA (PROP)**	**FD MICRONESIA (SKEW)**	**DAWR Bank Fishing (BIOM)**	**DAWR Bank Fishing (SIZE)**	**DAWR CREEL (PROP)**	**DAWR CREEL (SIZE)**	**FD consensus**
Acanthurus lineatus	ns	-0.2	no data	no data	ns	-0.04	2
Aprion virescens	ns	0.94	-3.1	-9.8	-0.2	0.11	3
Bolbometopon muricatum	ns	no data	no data	no data	no data	no data	6
Caranx melampygus	0.51	ns	no data	no data	0.89	0.13	4
Cephalopholis argus	ns	0.14	no data	no data	no data	no data	2
Cheilinus undulatus	no data	no data	no data	no data	no data	no data	6
Chlorurus frontalis	ns	ns	no data	no data	ns	ns	5
Chlorurus microrhinos	-0.51	-0.21	no data	no data	-2.6, 2.43	-0.43	1
Chlorurus spilurus	0.26; 0.19	no data	no data	no data	ns	0.07	4
Epinephelus fasciatus	no data	no data	15.1	-1.85	-0.09	-0.07	3
Epinephelus merra	0.05	no data	no data	no data	-0.11	-0.04	3
Hipposcarus longiceps	-1.14	0.13	no data	no data	0.07	ns	5
Kyphosus cinerascens	ns	-0.08	no data	no data	ns	ns	5
Lethrinus olivaceus	-0.42	0.24	no data	no data	-0.09	ns	3
Lethrinus rubrioperculatus	no data	ns	-18.6	-2.5	-18.1; 14.1	ns	1
Lethrinus xanthochilus	ns	ns	no data	no data	6.4,-14.4	0.12	4
Lutjanus fulvus	0.17	ns	no data	no data	ns	ns	4
Lutjanus gibbus	ns	ns	ns	-6.36	ns	ns	2
Lutjanus kasmira	no data	no data	ns	-2.3	-0.03	-0.04	2
Monotaxis grandoculis	ns	ns	no data	no data	ns	ns	5
Mulloidichthys flavolineatus	ns	ns	no data	no data	0.03	0.04	5
Naso lituratus	-0.55	0.12	no data	no data	-0.04	ns	3
Naso unicornis	ns	0.27	no data	no data	-0.88	ns	3
Scarus psittacus	no data	no data	no data	no data	-0.02	-0.19	3
Scarus schlegeli	ns	ns	no data	no data	ns	ns	5
Siganus argenteus	-0.54	0.21	no data	no data	0.08	-0.08	2
Siganus punctatus	ns	0.11	no data	no data	no data	no data	5
Variola louti	-1.66, 1.55	ns	-1.54	-5.1	-0.04	-0.05	1

Outcome key	**Response**
1	decline in (%) biomass strongest response
2	decline in size strongest response
3	decline equal in size and % biomass
4	increase in (%) biomass with mixed size response
5	mainly non-significant trends
6	insufficient data

Table 2. Results from statistical tests examining responses to fishing pressure gradients based upon fisheries-dependent datasets. Numbers in each box refer to effect sizes associated with each statistical test (see Figures 3-7 for visual relationships quantified here). Grey colors indicate insufficient data were available, yellow boxes indicate a non-significant relationship, red boxes indicate a decline in biomass or size structure at differing thresholds (dark red, P<0.05; light red, P<0.01), green boxes indicate increases in size structure or biomass with dark and light shades indicating similar thresholds. See methods for a description of each datasets and statistical relationship examined in greater detail. The last column represents an consensus of the species responses across all datasets based upon the authors' evaluations.



Target species	**GLTMP-Resilience-MPA (BINOMIAL)**	**GLTMP-MPA (BIOM)**	**FI MICRONESIA (PROP)**	**Guam-PH-SPC-MPA (BIOM)**	**Guam-PH-SPC-MPA (SIZE)**	**NOAA-CREMP-Habitat**	**Guam-Stereovideo-(BiomassXFishingPressure)**	**Guam-StereoVideo-(BiomassMPA)**	**Guam-Stereovideo-(SizeXFishing Pressure)**	**Guam-Stereovideo-(SizeXMPA)**	**FI consensus**
Acanthurus lineatus	ns	ns	0.68	-0.16	ns	ns	ns	ns	-0.08		4
Aprion virescens	ns	no data	ns	no data	no data	no data	ns	ns	no data	no data	3
Bolbometopon muricatum	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	6
Caranx melampygus	2.94	no data	ns	0.04	ns	1.17	ns	0.95	no data	no data	1
Cephalopholis argus	2.1	ns	ns	0.02	ns	no data	ns	ns	no data	no data	1
Cheilinus undulatus	no data	no data	ns	no data	no data	no data	ns	ns	no data	no data	6
Chlorurus frontalis	no data	no data	ns	ns	14.48	-1.31	ns	ns	-0.25	0.12	2
Chlorurus microrhinos	1.16	no data	-3.04	0.13	ns	no data	-0.97	1.74	-0.31	0.24	1
Chlorurus spilurus	ns	0.76	1.51	0.07	1.31	-2.1	ns	ns	-0.12	0.15	3
Epinephelus fasciatus	no data	ns	ns	0.002	no data	no data	ns	ns	ns	ns	5
Epinephelus merra	no data	ns	ns	ns	no data	no data	no data	no data	no data	no data	5
Hipposcarus longiceps	ns	no data	-0.41	0.03	ns	ns	-0.82	1.56	-0.60	0.66	3
Kyphosus cinerascens	ns	no data	ns	ns	ns	no data	ns	ns	ns	0.31	5
Lethrinus olivaceus	ns	no data	ns	0.03	ns	no data	no data	no data	no data	no data	5
Lethrinus rubrioperculatus	no data	no data	no data	no data	no data	no data	no data	no data	no data	no data	6
Lethrinus xanthochilus	ns	no data	ns	0.02	ns	no data	no data	no data	no data	no data	5
Lutjanus fulvus	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	5
Lutjanus gibbus	ns	no data	ns	0.02	17.4	no data	ns	ns	ns	ns	2
Lutjanus kasmira	no data	no data	ns	no data	no data	no data	no data	no data	no data	no data	2
Monotaxis grandoculis	ns	ns	0.65	0.33	6.05	no data	-0.44	ns	ns	ns	3
Mulloidichthys flavolineatus	no data	no data	ns	no data	no data	no data	ns	ns	no data	no data	5
Naso lituratus	ns	0.18	2.11	ns	1.5	ns	ns	ns	-0.08	ns	2
Naso unicornis	ns	ns	0.44	0.06	5.7	-0.23	-0.2	ns	ns	ns	3
Scarus psittacus	ns	ns	0.66	0.11	ns	-0.7	ns	ns	-0.12	0.12	3
Scarus schlegeli	ns	0.08	0.75	ns	2.78	-0.49	ns	ns	-0.12	0.14	2
Siganus argenteus	3.21	no data	ns	ns	ns	no data	ns	ns	no data	no data	5
Siganus punctatus	no data	no data	ns	no data	no data	no data	no data	no data	no data	no data	6
Variola louti	no data	no data	-0.09	0.01	ns	no data	-0.83	ns	no data	no data	1

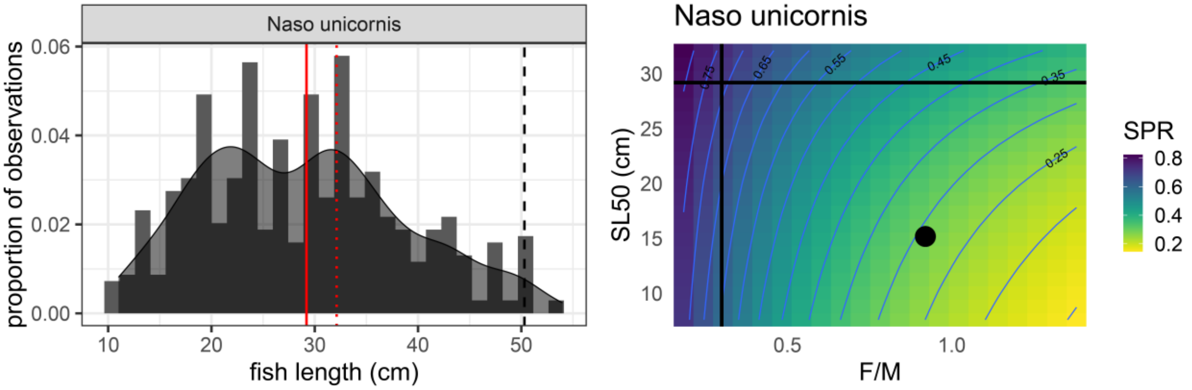
Outcome key	**Response**
1	decline in (%) biomass strongest response
2	decline in size strongest response
3	decline equal in size and % biomass
4	increase in (%) biomass with mixed size response
5	mainly non-significant trends
6	insufficient data

Table 3. Results from statistical tests examining responses to fishing pressure gradients based upon fisheries-independent datasets. Numbers in each box refer to effect sizes associated with each statistical test (see Figures 3-7 for visual relationships quantified here). Grey colors indicate insufficient data were available, yellow boxes indicate a non-significant relationship, red boxes indicate a decline in biomass or size structure at differing thresholds (dark red, P<0.05; light red, P<0.01), green boxes indicate increases in size structure or biomass with dark and light shades indicating similar thresholds. See methods for a description of each datasets and statistical relationship examined in greater detail. The last column represents an consensus of the species responses across all datasets based upon the authors' evaluations.

Spawning potential ratio

SPR analyses were performed for 14 species that were selected as targets in the present study and also had locally-derived life-history data (Table 4). SPR analyses revealed that only 3 of 14 (21%) species had predicted SPR values below 0.3, or the suggested 30% management threshold: *Naso unicornis*, *Acanthurus lineatus*, and *Hipposcarus longiceps* (Table 4). Interestingly, these three species all had mixed trends from FI and FD data sources, with limited clarity regarding whether size and biomass trends were increasing or decreasing across space and through time. In contrast, many species associated with clear declining trends from FI and FD data sources had SPR values larger than 0.3, often much larger: *Variola louti*, *Chlorurus microrhinos*, *Lethrinus rubrioperculatus*. In sum, the perceived status of target species from SPR analyses did not align well with the status reported by FI and FD data (*see discussion*). However, several SPR metrics did align well with the FI and FD results.

SPR results were visualized for the six representative species noted above and showcased how two metrics helped to interpret the impact of fishing pressure on each species: 1) overall fishing mortality (F/M), and 2) size-at-capture (SL_{50}) (Figure 9). Using size-frequency histograms as a basis, increasing fishing mortality served to reduce the presence of all sizes classes in landings, and depress SPR while having less truncation, or skewness, in the size frequency histograms (Figure 8b, *Chlorurus microrhinos*). For species such as the large-bodied parrotfish *Chlorurus microrhinos*, SPR was more dynamic while moving across a gradient in F/M compared to a gradient of size-at-capture (SL_{50}) (Figure 8b). In contrast, for species such as the unicornfish *Naso unicornis*, SPR was similarly dynamic while moving across gradients of F/M or SL_{50} (Figure 8a). These findings resonated with FD and FI results whereby the large parrotfish had declining biomass as the primary response, while the unicornfish had trends attributed to both size and biomass. Similar SPR-derived trends were documented for all target species that had local life-history data (Table 4). For each species, size-at-capture can be compared to size-at-reproduction (SL_{50} to L_{50}) to appreciate size-based responses to fishing pressure, while fishing mortality (F/M) can be compared against the recommended 30% management threshold to appreciate biomass-based responses to fishing pressure (Table 4). We summarize that species status assessments were mostly different between SPR analyses and examinations of FD and FI data, however, key attributes of SPR analyses aligned with FD and FI trends (discussion). These findings reinforce the utility of understanding the nature of species responses in terms of biomass declines versus size declines when discussing potential management options.


Naso unicornis
proportion of observations
0.06
0.04
0.02
0.00
10
20
30
40
50
fish length (cm)
Naso unicornis
SL50 (cm)
30
25
20
15
10
0.5
1.0
F/M
0.75
0.65
0.55
0.45
0.35
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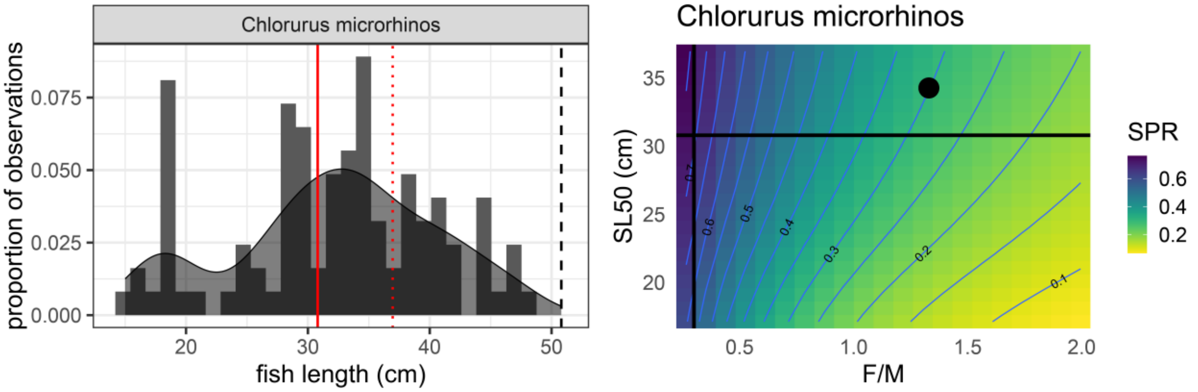
SPR
0.8
0.6
0.4
0.2

a)


Chlorurus microrhinos
proportion of observations
0.075
0.050
0.025
0.000
20
30
40
50
fish length (cm)
Chlorurus microrhinos
SL50 (cm)
35
30
25
20
0.5
1.0
1.5
2.0
F/M
0.7
0.6
0.5
0.4
0.3
0.2
0.1
SPR
0.6
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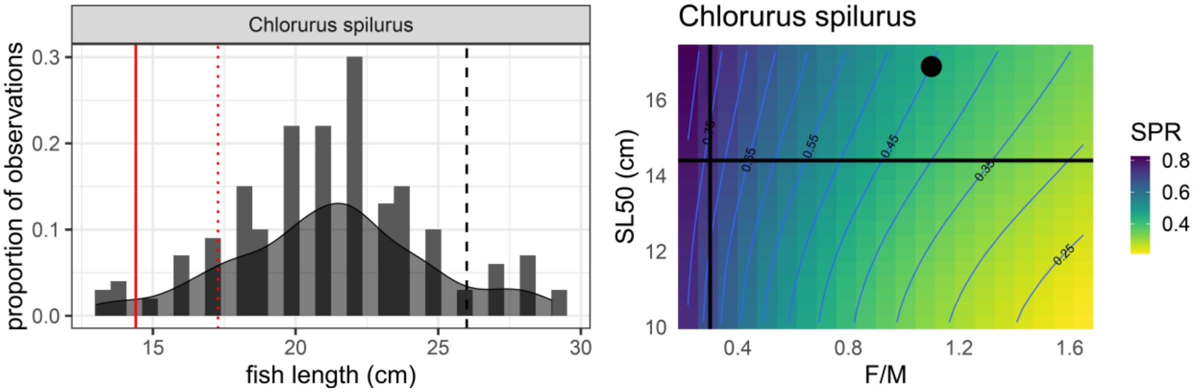
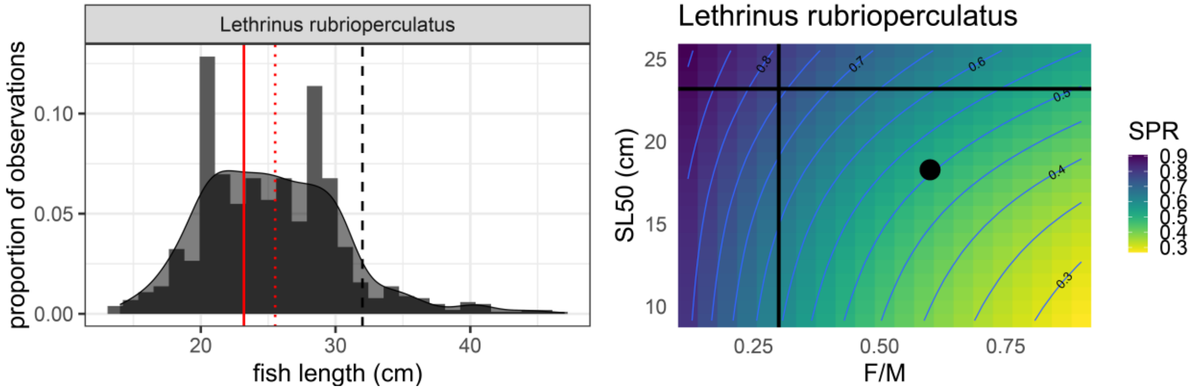
0.2

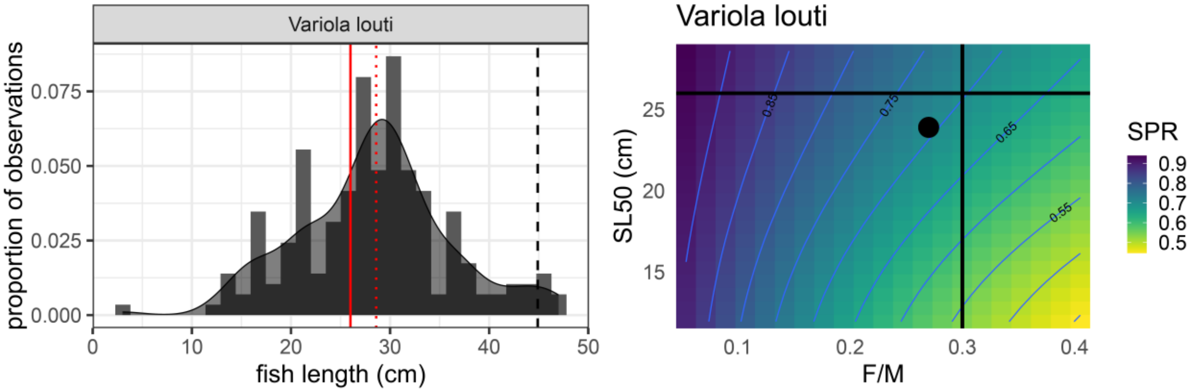
b)


Chlorurus spilurus
proportion of observations
0.3
0.2
0.1
0.0
15
20
25
30
fish length (cm)
Chlorurus spilurus
SL50 (cm)
16
14
12
10
0.4
0.8
1.2
1.6
F/M
0.75
0.65
0.55
0.45
0.35
0.25
SPR
0.8
0.6
0.4

c)



d)



e)

Figure 9a-e. Results from spawning-potential-ratio (SPR) assessments for five representative species with locally-derived life-history data. For each species, histograms (left) depict the sizes at capture from freedive and bottomfishing landings associated with DAWR creel data 2010-present and a recently completed UOGML thesis in 2021 (methods). Red lines indicate the L50 (solid) and SL50 (dashed), or the sizes at 50% maturity and selectivity. Black line (dashed) indicates the asymptotic length, or the length a typical fish would reach at maximum age. Three key outputs from SPR analyses are shown on the contour plot (right): F/M, or fishing mortality divided by natural mortality, SPR, or the ratio of the modelled spawning biomass compared to unfished spawning biomass, and SL50. The large black dot represents the current prediction based upon landings, while the contours provide estimates of SPR that would emerge if overall fishing pressure were reduced (F/M), or if size-regulations were established to change the SL50. Horizontal reference line indicates the L50 to show the relationship between harvest size and size at maturity. The vertical reference line represents 0.3, or generalized guidance suggested that F/M should not exceed this threshold for most species.

Target species	K	L_{inf}	L_{50}	L_{95}	SL_{50}	SL_{95}	F/M	SPR	SPR consensus
Variola louti	0.22	44.9	26	31.8	23.9	34.72	0.27	0.71	4
Naso unicornis	0.23	50.3	29.2	33.9	15.18	21.01	0.92	0.29	3
Chlorurus spilurus	0.96	26*	14.4	18.1	16.88	21.71	1.1	0.44	2
Chlorurus microrhinos	0.23	50.8	30.8	36.8	34.27	51.4	1.33	0.42	2
Lethrinus rubrioperculatus	0.8	31.5	23.2	27.8	18.29	22.47	0.6	0.51	2
Acanthurus lineatus	1.16	21*	17.4	20	12.72	16.59	4.33	0.1	2
Caranx melampygus	0.21	59.4	30.4	33.3	18.26	30.28	0.18	0.73	1
Chlorurus frontalis	0.34	41.6	24	26.3	24.26	34.45	0.36	0.69	4
Hipposcarus longiceps	0.44	46.2	32.9	40.6	16.23	20.33	1.19	0.17	3
Mulloidichthys flavolineatus	0.72	27*	15.8	19.6	11.98	16.16	0	1	4
Naso lituratus	0.29	25*	14.5	22.8	14.12	18.61	0.69	0.5	2
Scarus schlegeli	0.46	35*	19.7	24.9	17.59	24.88	0.32	0.67	4
Siganus argenteus	0.42	30.1	21.8	28	14.29	18.59	0.77	0.32	3
Scarus psittacus	1.01	29*	10.3	20.7	13.53	16.84	1.1	0.35	2

Outcome key	Response
1	SL50 << L50
2	F/M>>0.3
3	SL50 and F/M response similar
4	none

Table 4. Results from spawning-potential-ratio (SPR) modeling used to assessed each target species that had local life-history data available (see Figure 8 for linked example graphs). Key metrics for each species included K-growth rate, L_{inf}-asymptotic size, L_{50}-size at 50% maurity, L_{95}-size at 95% maturity, SL_{50}-size at 50% fishing selectivity, SL_{95}-size at 95% fishing selectivity, F/M-ratio of fishing-to-natural mortality, and estimated SPR. The last column represents an consensus of the species responses based upon the authors' evaluations. This is ***not*** *based upon the numerical value of SPR with respect to any threshold, but rather based upon two key attributes of the modeling outcomes that may help inform potential management: 1) SL_{50} versus L_{50} – size at harvesting compared to size at maturity, and 2) F/M with respect to the 0.3 threshold to interpret the relative strength of fishing mortality. *Indicates small-bodied, fast-growing species with highly-asymptotic and variable length-at-age profiles(see discussion and Appendix 2). L_{inf} for these species was interpolated from observation data using the relationships that existed from large-bodied species as a precautionary approach (Appendix 2).*

Discussion

This study provided a unique opportunity to conduct data-rich examinations for 26 target coral-reef fishes that contributed disproportionally to landings on Guam over the past several decades. The culmination of 9 unique fisheries-dependent and fisheries-independent datasets provided a consensus assessment for each species and revealed how each species may respond to fishing pressure gradients. We reported declining biomass and/or size trends for 21 of 26 species with sufficient FI or FD data for examinations, comprised of mainly large-bodied species in their respective families. These findings generally agree with studies over the past decade reporting: i) declines in many target species sizes and biomass on Guam (Taylor et al. 2014, Houk et al. 2018, Taylor et al. 2022), ii) regionally low, often lowest, fish biomass for many species and overall fish biomass on Guam compared to other Pacific islands (Williams et al. 2012, MacNeil et al. 2015, Houk et al. 2021), and iii) significantly lower catch success and observed biomass on Guam's leeward, more accessible reefs compared to windward, wave-exposed reefs (Houk et al. 2022, Taylor et al. 2022). Yet, the consensus approach used in this study was novel and provided guidance for a large suite of target species not previously available.

As fishing pressure increases, the target species that dominate landings can shift, and some species can become "winners" or "losers" based upon their biological capacity to cope with and recover from exploitation (Houk et al. 2021). For instance, the results suggested that three of the selected target species have experienced highly significant declines in proportional biomass through time or across spatial fishing gradients: the large-bodied parrotfish *Chlorurus microrhinos*, the large-bodied grouper *Variola louti*, and large-bodied emperor *Lethrinus rubrioperculatus*. Identifying these sensitive species among multi-species fisheries can be difficult because sensitive populations may be compromised by the time regular monitoring or data collection events begin. This has been previously hypothesized for the largest target species that were selected for assessments but did not have sufficient data: the bumphead parrotfish (*Bolbometopon muricatum*) and the Napolean wrasse (*Cheilinus undulatus*). Meanwhile, other desirable species have shown non-significant trends, size-based responses, or both size-and-biomass based trends equally. These contrasting responses helped to identify management interventions that may be best suited for each target species.

Ideally, management interventions would be designed to match the biology of each target species. Therefore, our outcomes were linked with two broad classes of management interventions, size-based or effort-based. Species with strong size-based responses to fishing pressure often represented "winners" that remained dominant in landings despite size shifts, discussed above. These species represent ideal candidates for size-based policies as one means of potential management (i.e, minimum, maximum, or slot-based). Meanwhile, species with strong biomass-based responses represent ideal candidates for management interventions that control overall fishing effort (gear-restrictions, marine protected areas, commercial-versus-subsistence fishing pressure, spawning seasons, and other similar approaches that address entire populations). Therefore, our results can provide a guide for discussing the status and potential management of target species that will soon begin as part of the Guam fisheries management planning process that includes fishers, managers, scientists, and other sectors alike.

SPR modelling versus FI and FD trends

There were several factors behind the disparate nature of species assessment outcomes from SPR analyses compared to FI and FD trends. First, SPR modeling is highly sensitive to several life-history parameters, most notably L_{inf}, or the mean asymptotic length individuals, and K, or the growth coefficient (i.e., the relative rate at which fish approach L_{inf}). For example, reducing the L_{inf} of *Naso unicornis* by just 2 cm, from 50 cm as estimated by unconstrained fitting of local life-history data used here to 48 cm, resulted in a 34% increase in SPR (0.39 versus 0.29). Such sensitivity is discouraging because life-history parameters are highly dynamic within and across Pacific islands and, therefore, life-history traits for target coral-reef fishes will vary considerably even within islands (Gust et al. 2002, Taylor and Choat 2014). We reviewed how parameters such L_{inf} are more sensitive to local environmental conditions (i.e., inner versus outer reef) and geography (latitude and longitude) than to differing fishing pressure regimes (Appendix 2). Thus, when life-history data are collected from non-representative environments or incorporated from non-local sources, the SPR findings can shift significantly. Moreover, because of this variability, a locality-specific set of trait values for any species does not truly exist; hence, the objective is to summarize species' biology as best as possible.

Second, modelling for some large-bodied target species with significant biomass declines, or effect sizes, reported in many datasets had SPR outcomes above the 0.3 recommended management threshold. SPR is rooted in the theory that larger individuals have exponentially more reproductive output, or the well-known exponential relationships between length, weight, and gonad sizes (Barneche et al. 2018). Thus, when fishing pressure resulted in significant truncation of size-at-capture compared to L_{inf} values, SPR was diminished the most (i.e., *Hipposcarus longiceps* with $SL_{50} << L_{50}$, Table 4). In support, previous studies have revealed positive relationships between a simple metric of skewness (or truncation) of size distributions of fish landings, SPR, and the reported population status (Houk et al. 2017, Houk et al. 2021). Yet, FI and FD data revealed that numerous species had little size truncation but highly significant biomass declines. Interestingly, these sensitive species described above often had unexpectedly large SPR outcomes (i.e., *Variola louti* with SPR of 0.71 despite highly significant declines in biomass from FD and FI data). We do not speculate further regarding the biological mechanisms of biomass-versus-size responses among diverse, multispecies coral-reef fisheries, but variable density dependence has previously been observed and discussed (Houk et al. 2018, Houk et al. 2021). For instance, many species attributes are known to dictate population dynamics and could contribute to variable density dependence such as home-range sizes, ontogeny, competitive interactions associated with differing life stages, diets, and many others.

Third, the logistic curve fitting process often rendered values for L_{inf} that were below the 90th percentile of observed sizes in landings for several species, especially small-bodied species. The variability around L_{inf} can differ widely for species, often ± 50% of the mean calculated by the logistic curve fitting process. In addition, many small-bodied species have a rapid rise in length across relatively small age intervals, followed by long lifespans. This results in high growth (K) and/or low mortality (M), or diminished M/K inputs to SPR modelling. Diminished M/K values coupled with high L_{inf} variability resulted in SPR outcomes of 1, or no fishing pressure being exerted on the species, which was unrealistic (Appendix 2). Therefore, we caution the use of SPR for small-bodied species.

The important conclusion is that SPR outcomes often provided inconsistent results with the FI and FD outcomes, however, SPR metrics describing whether size, biomass, or both responses would be most important for managing each species often aligned well with FI and FD size-and-biomass recommendations. Thus, using SPR as a tool to identify potential management interventions appeared to have merit for data-poor fisheries that might not have extensive FI and FD data and are perceived to be in decline based upon stakeholder opinions.

Conclusions

Our study was designed to support both species assessments and potential management interventions that are part of the ongoing Guam fisheries management planning process (FMP). The rare ability to incorporate extensive FI and FD data sources and take a consensus approach to evaluate target species provided unprecedented, high-resolution outcomes for evaluating multispecies coral-reef fisheries. This unique foundation afforded a deeper understanding of data-poor stock assessments that revealed the strengths and weaknesses of SPR modelling. SPR was ideal for larger-bodied species with strong compensatory density dependence (i.e., size-and-age truncation) when exposed to fishing pressure. Coupled with locally-derived life-history data, assessment for these species were similar to FI and FD data. However, for most small-bodied species and large-bodied species with limited size-age truncation, SPR appeared to provide false outcomes that often did not match FI and FD data, or anecdotal perceptions of the species' status. Therefore, for the Guam FMP process we recommend a stronger reliance on the FD and FI outcomes to interpret species status assessments. However, for potential management interventions, both approaches may provide similar guidance.

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Appendix 1

Species	***Family***	***Source***	***Location***	***Data type***	***sample si***	***Linf***	***K***	***L0***	***Linf_uncon***	***K_uncon***	***L0_uncon***	***t0***	***M***	***Lifespan***	***a***	***b***	***seasonality***	***L50***	***L95***	***t50***	***t95***	***L Δ50***	***L Δ95***	***sexuality***	***GSImax***	***dimorphic growth?***
Naso_unicornis	Acanthuridae	Taylor et al. 2014 J	Guam	raw_oto_go	247	493	0.22	50	503	0.23	89	-0.48	0.181	23	5.61E-05	2.812	no	292	339	3.2	5.7	NA	NA	gonochore	1.5	No
Naso_lituratus	Acanthuridae	Taylor et al. 2014 J	Guam	raw_oto_go	126	204	0.93	50	227	0.29	129	-0.30	0.199	21	3.58E-06	3.369	no	145	228	2.1	3.9	NA	NA	gonochore	2	No
Caranx_melampygus	Carangidae	unpublished	Guam	raw_oto_go	151	533	0.38	50	594	0.21	167	-0.26	0.323	13	2.76E-05	2.931	likely	304	333	1.9	2.1	NA	NA	gonochore	3.8	No
Epinephelus_polyphekadion	Epinephelinae	Rhodes et al. 2011,	Pohnpei_C	raw_oto_go	718	447	0.25	25	456	0.23	53	-0.14	0.167	25	6.85E-06	3.143	high	352	412	6.4	9.3	NA	NA	gonochore	4	No
Plectropomus_areolatus	Epinephelinae	Rhodes et al. 2013,	Pohnpei_C	raw_oto_go	415	455	0.64	40	NA	NA	NA	-0.31	0.350	12	4.84E-05	2.822	high	366	385	2.3	7.8	NA	NA	gonochore	3	Yes
Sargocentron_spiniferum	Holocentridae	unpublished	Saipan	raw_oto_go	345	270	0.25	60	410	0.08	118	-1.01	0.232	18	2.03E-05	3.024	NA	NA	NA	NA	NA	NA	NA	gonochore	6	No
Sargocentron_tiere	Holocentridae	unpublished	Saipan	raw_oto_go	316	193	0.56	60	210	0.21	133	-0.67	0.382	11	5.02E-05	2.847	NA	NA	NA	NA	NA	NA	NA	gonochore	8	Yes
Calotomus_carolinus	Labridae	Taylor & Choat 201	Guam	raw_oto_go	34	263	0.91	15	266	1.52	93	-0.07	1.420	3	1.05E-05	3.146	no	168	208	1.1	2.3	213	259	protogyny	2	Yes
Cetoscarus_ocellatus	Labridae	Taylor & Choat 201	Pohnpei	raw_oto_go	47	402	0.59	15	414	0.45	86	-0.07	0.350	12	1.88E-05	3.006	no	323	390	3.1	4.8	375	469	protogyny	4	Yes
Chlorurus_frontalis	Labridae	Taylor & Choat 201	Guam	raw_oto_go	83	372	0.71	15	416	0.34	141	-0.06	0.382	11	9.13E-06	3.157	no	240	263	1.6	2.7	343	561	protogyny	7	Yes
Chlorurus_microrhinos	Labridae	Taylor & Choat 201	Guam	raw_oto_go	80	457	0.34	15	508	0.23	83	-0.10	0.350	12	2.01E-05	3.019	no	308	368	3.7	5.4	378	468	protogyny	5	Yes
Chlorurus_spilurus	Labridae	Taylor & Choat 201	Guam	raw_oto_go	347	218	0.95	15	212	0.96	17	-0.08	0.468	9	1.28E-05	3.113	no	144	181	1.3	2.4	207	236	protogyny	5	Yes
Scarus_altipinnis	Labridae	Taylor & Choat 201	Guam	raw_oto_go	53	339	0.66	15	370	0.33	138	-0.07	0.300	14	1.26E-05	3.086	no	251	286	2.9	3.1	337	512	protogyny	3	Yes
Scarus_forsteni	Labridae	Taylor & Choat 201	Guam	raw_oto_go	80	281	0.88	15	290	0.57	111	-0.06	0.350	12	3.37E-05	2.918	no	216	251	1.8	2.6	271	322	protogyny	3	Yes
Scarus_ghobban	Labridae	Taylor & Choat 201	Pohnpei	raw_oto_go	31	310	1.41	15	320	0.76	157	-0.04	0.705	6	8.90E-06	3.126	no	NA	NA	NA	NA	314	361	protogyny	NA	Yes
Scarus_psittacus	Labridae	Taylor & Choat 201	Guam	raw_oto_go	114	207	0.91	15	203	1.01	-10	-0.08	0.705	6	2.01E-05	3.007	no	103	207	1.4	3.4	193	236	protogyny	4	Yes
Scarus_rubroviolaceus	Labridae	Taylor & Choat 201	Guam	raw_oto_go	57	376	0.66	15	471	0.26	94	-0.06	0.350	12	1.90E-05	3.021	no	271	279	1.9	2.2	319	367	protogyny	4.6	Yes
Scarus_schlegeli	Labridae	Taylor & Choat 201	Guam	raw_oto_go	116	252	1.03	15	281	0.46	109	-0.06	0.527	8	5.01E-05	2.843	no	197	249	2.0	3.3	209	226	protogyny	2	Yes
Hipposcarus_longiceps	Labridae	Taylor & Cruz 2017	Guam	raw_oto_go	265	434	0.79	15	462	0.44	163	-0.04	0.421	10	2.11E-05	2.986	no	329	406	2.4	4.3	401	490	protogyny	7	Yes
Bolbometopon_muricatum	Labridae	Taylor et al. 2018	Solomon Is	raw_oto_go	243	1070	0.15	10	1070	0.15	12	-0.07	0.144	29	1.17E-06	3.409	no	600	750	6.0	8.0	NA	NA	gonochore	10	Yes
Lethrinus_harak	Lethrinidae	Taylor & McIlwain	Guam	raw_oto_go	413	281	0.27	90	280	0.27	79	-1.25	0.323	13	1.12E-05	3.101	no	208	252	3.8	6.1	242	301	protogyny	5.6	No
Lethrinus_obsoletus	Lethrinidae	Taylor et al. 2017 I	Saipan	raw_oto_go	723	251	0.60	30	270	0.32	114	-0.22	0.323	13	2.39E-05	2.956	no	229	246	3.8	4.9	NA	NA	gonochore	2	No
Lethrinus_atkinsoni	Lethrinidae	Trianni et al. 2023	Saipan	raw_oto_go	785	263	0.61	17	298	0.25	119	-0.11	0.232	18	1.02E-05	3.144	no	209	235	3.3	5.2	NA	NA	gonochore	4.5	No
Lethrinus_rubrioperculatus	Lethrinidae	Trianni 2011	Saipan	raw_oto_go	174	315	0.80	107	315	0.80	107	-0.52	0.527	8	2.30E-04	2.922	March_April	232	278	1.2	NA	290	NA	protogyny	5	No
Lethrinus_xanthochilus	Lethrinidae	Taylor et al. 2018 F	Tutuila	raw_oto_go	236	402	0.64	30	405	0.59	55	-0.12	0.220	19	2.30E-05	2.944	NA	300	399	2.1	4.7	373	419	protogyny	25	No
Lethrinus_olivaceus	Lethrinidae	Filous et al. 2022 J	Rangiroa	raw_oto_go	516	800	0.18	120	800	0.18	120	-0.82	0.300	14	1.06E-04	2.99	_predictable_	380	470	3.0	4.0	450	470	protogyny	6	No
Lutjanus_gibbus	Lutjanidae	Taylor et al. 2018 F	Tutuila	raw_oto_go	236	329	0.46	35	331	0.16	205	-0.25	0.154	27	1.90E-04	2.608	NA	249	290	3.2	4.8	NA	NA	gonochore	38	Yes
Lutjanus_bohar	Lutjanidae	Taylor in prep	Guam	model_proj_	NA	623	0.11	50	628	0.1	82	-0.76	0.088	47	2.64E-06	3.314	NA	NA	NA	NA	NA	NA	NA	gonochore	NA	No
Macolor_niger	Lutjanidae	Taylor in prep	Guam	model_proj_	NA	490	0.24	50	505	0.11	210	-0.45	0.096	43	2.27E-05	2.94	NA	NA	NA	NA	NA	NA	NA	gonochore	NA	No
Mulloidichthys_flavolineatus	Mullidae	Reed & Taylor 202	Saipan	raw_oto_go	273	245	1.25	0	261	0.72	96	0.00	0.847	5	2.70E-05	2.918	no	158	196	0.4	1.6	NA	NA	gonochore	3	Yes
Parupeneus_barberinus	Mullidae	Reed & Taylor 202	Saipan	raw_oto_go	170	266	1.28	0	335	0.36	134	0.00	0.847	5	2.59E-05	2.937	no	154	172	0.9	1.3	NA	NA	gonochore	1	Yes
Siganus_argenteus	Siganidae	Taylor et al. 2017	Saipan	raw_oto_go	425	274	0.90	65	301	0.42	133	-0.30	0.563	8	7.01E-06	3.182	ce_annually_lu	218	280	1.3	2.5	NA	NA	gonochore	9	Yes
Siganus_punctatus	Siganidae	Rhodes et al. 2017	Pohnpei	raw_oto_go	281	241	1.66	0	240	1.69	-5	0.00	0.527	8	1.65E-05	3.075	ce_annually_lu	214	272	1.7	4.6	NA	NA	gonochore	10	No
Acanthurus_blochi	Acanthuridae	Taylor et al. under	Guam	raw_oto_go	28	304	0.35	35	312	0.3	62	-0.35	0.527	8	3.26E-05	2.973	NA	*222*	*271*	*3.3*	*3.6*	NA	NA	gonochore	NA	No
Acanthurus_guttatus	Acanthuridae	Taylor et al. under	Guam	raw_oto_go	116	162	0.65	35	177	0.3	81	-0.37	0.181	23	9.22E-06	3.247	more activity i	*117*	*128*	*1.6*	*2.3*	NA	NA	gonochore	NA	No
Acanthurus_lineatus	Acanthuridae	Taylor et al. under	Guam	raw_oto_go	187	190	1.21	35	191	1.16	40	-0.17	0.220	19	2.22E-05	3.028	more activity i	*174*	*200*	*2*	*3.3*	NA	NA	gonochore	NA	No
Acanthurus_nigricauda	Acanthuridae	Taylor et al. under	Guam	raw_oto_go	558	219	0.61	35	235	0.34	102	-0.29	0.246	17	1.65E-05	3.088	no	*183*	*209*	*3*	*4.8*	NA	NA	gonochore	3	No
Acanthurus_olivaceus	Acanthuridae	Taylor et al. under	Guam	raw_oto_go	100	212	0.98	35	215	0.67	103	-0.18	0.279	15	2.33E-05	3.012	NA	*168*	*186*	*1.4*	*2.0*	NA	NA	gonochore	NA	No
Acanthurus_triostegus	Acanthuridae	Taylor et al. under	Guam	raw_oto_go	98	164	0.58	35	170	0.4	64	-0.41	0.330	12	1.59E-05	3.113	more activity i	*112*	*142*	*1.3*	*2.0*	NA	NA	gonochore	9	No
Acanthurus_xanthopterus	Acanthuridae	Taylor et al. under	Guam	raw_oto_go	60	354	0.35	35	371	0.27	79	-0.30	0.350	12	6.76E-05	2.825	NA	*276*	*297*	*4*	*4.9*	NA	NA	gonochore	NA	No
Ctenochaetus_striatus	Acanthuridae	Taylor et al. under	Guam	raw_oto_go	115	162	1.26	35	165	0.73	76	-0.19	0.246	17	2.00E-05	3.026	NA	*134*	*161*	*1.1*	*3.8*	NA	NA	gonochore	NA	No
Zebrasoma_velifer	Acanthuridae	Taylor et al. under	Guam	raw_oto_go	42	220	0.29	35	230	0.2	75	-0.60	0.190	22	1.39E-04	2.657	NA	*159*	*175*	*3.8*	*4.2*	NA	NA	gonochore	NA	No
Naso_vlamingi	Acanthuridae	Taylor et al. under	Guam	raw_oto_go	66	270	1.10	50	266	1.35	11	-0.19	0.468	9	2.66E-04	2.527	NA	*258*	*306*	*3*	*3.7*	NA	NA	gonochore	NA	No
Naso_tonganus	Acanthuridae	Taylor et al. under	Guam	raw_oto_go	87	539	0.29	50	543	0.27	69	-0.34	0.220	19	1.22E-04	2.678	NA	*357*	*378*	*3.6*	*3.8*	NA	NA	gonochore	NA	No
Cheilinus_undulatus	Labridae	Kang et al in prep	Guam	raw_oto_go	113	1382	0.10	50	1604	0.07	168	-0.26	0.263	16	1.61E-02	3.0552	NA	*550*	*NA*	*NA*	*NA*	*785*	*833*	protogyny	2	Yes
Variola_louti	Epinephelinae	Schemmel and Dah	Guam	raw_oto_go	287	437	0.28	35	449	0.22	10.9	-0.20	0.370	17	NA	NA	winter_lunar	*260*	*318*	*2.6*	*5.8*	*355*	*450*	protogyny	6	No

Appendix 2

A primer on the use of life-history information in fisheries assessments

Many assessment techniques rely on life-history information (e.g., parameterization of growth trajectories, asymptotic size, lifespan, size at maturation, and mortality) to inform and structure their population models. Hence, the ability to model the population dynamics of harvested organisms is hinged on accurate life-history information. While life-history information exists for 36 target species in Guam and the Mariana Islands that are dominant in landings, there are hundreds of species that comprise total landings. Thus, reef fisheries are often considered data poor with respect to life-history. Further, almost nowhere in the tropics is there access to updated age structures and growth curves on an annually repeated basis such as those derived for industrial fisheries in temperate regions as standard practice to inform management. Because many assessment techniques rely so heavily on life-history information for their outcomes, accurate portrayals of the biology of species are imperative, rendering the accuracy and precision of life-history information a major concern.

Yet, even for species with available location-specific biological collections, concerns over the accuracy of life-history data may still exist. Concerns often stem from the idea that sustained long-term harvesting may alter key life-history metrics through truncation of size and age distributions. Key metrics include the length (L_{50}) and age at maturity (t_{50}), the mean asymptotic length (L_{inf}), and the coefficient of growth (K), which are influential inputs to population and harvesting models. While truncation through harvesting may shift some metrics, tropical coastal ecosystems are dynamic environments where life-history traits are known to vary substantially across environments (Gust et al. 2002; Robertson et al. 2005; Taylor et al. 2018). Therefore, a “true” value for any biological trait at a location is an artificial construct; what we must determine is the most realistic reflection that summarizes the biology within the region being studied. To do this, it is important to understand the relative magnitude of drivers of biological traits, both analytically and mechanistically.

Empirical collections facilitating the comparison of growth and longevity for fished and unfished areas from the same region are rare, but several examples from the tropical Pacific are displayed (Figure 1). Bluefin trevally (*Caranx melampygus*) from the Hawaiian Islands represents a prime example of size and age truncation in demographic samples of harvested fisheries, whereby the mean size and age in heavily fished Oahu was only 66 and 41%, respectively, of that sampled from nearby islands of Maui and Hawaii (Pardee et al. 2021). Nevertheless, the empirically-modelled asymptotic length changed between locations by less than 1% (Figure 1A). Similar patterns can be observed for other species from comparisons between MPAs and fished sites of the same island (Figure 1C-E, G-F) or between neighboring islands that differ in exploitation status (Figure 1F), where apparent changes in L_∞ are consistently within 6% and do not always result in truncation of trait values in the fished portion of populations. Such perceived differences can affect the outcomes of assessment models, but likely remain a low concern because of the asymptotic nature of the growth of tropical reef species.

While the effects of fishery truncation on perceived trait estimation is a concern, the magnitude of this effect is lower than the effects of habitat across small spatial scales (within islands) and the effects of temperature across latitudinal gradients on the life histories of reef fishes. For example, latitudinal comparisons of *C. melampygus* demonstrate that populations from the completely unfished but considerably warmer northernmost islands of the Mariana Archipelago are much younger (maximum observed age [t_{max}] decreases by 32%) and smaller (asymptotic length [*L*∞] decreases by 28%) compared to the exploited high-latitude Hawaiian Islands, a latitudinal pattern that extends through the western Pacific to Palau (Figure 1B). Meanwhile, changes in *L*∞ for the bullethead parrotfish (*Chlorurus spilurus*) occurring across regions within Guam (west versus south) irrespective of fishing pressure are more than twice as large as differences between adjacent sites of different fishing pressures (Figure 1D-E).

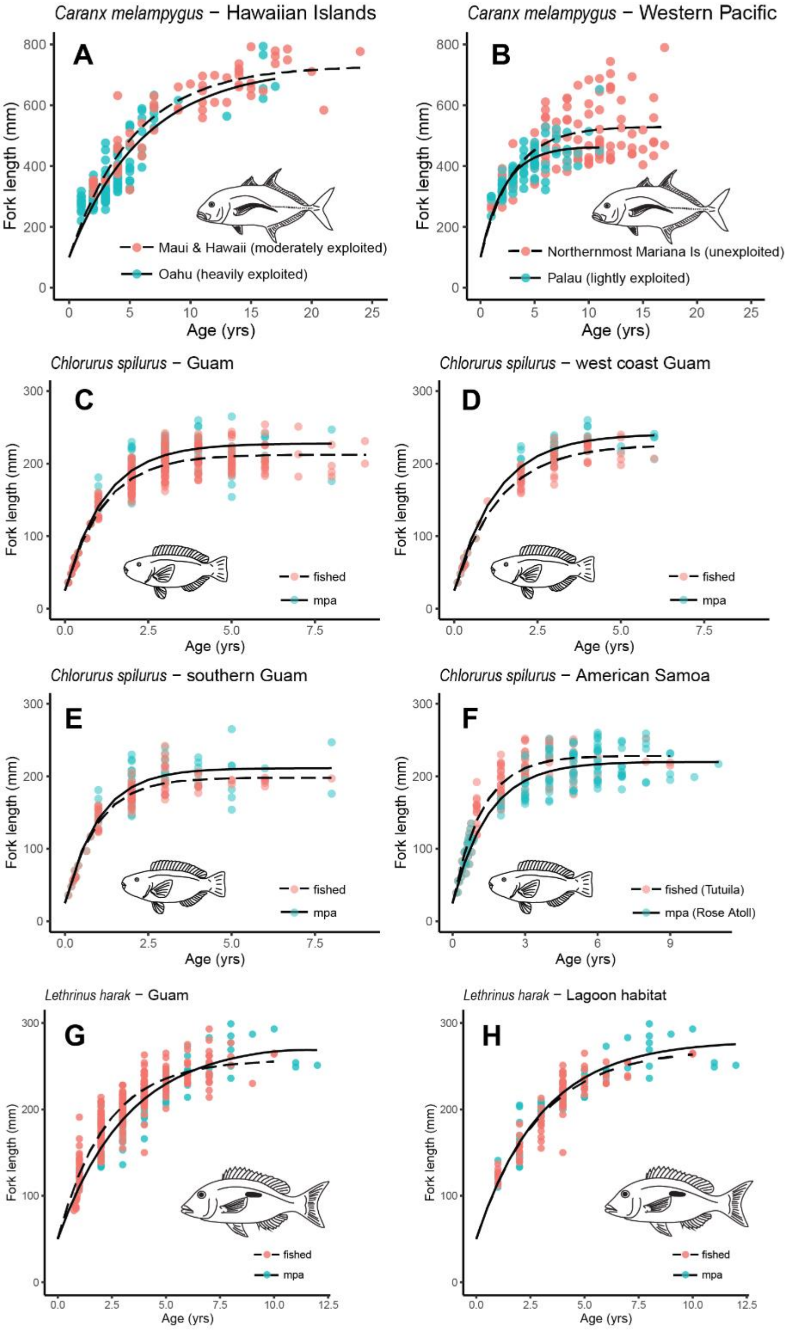

Figure 1. Comparisons of growth curves in the tropical Pacific. Caranx melampygus from (A) Hawaii state (heavily exploited Oahu versus moderately exploited Maui and Hawaii islands; Pardee et al. 2021) showing small perceived differences in asymptotic length (L∞) and (B) unfished or lightly regions of the western Pacific showing large differences in L∞ reflecting latitudinal change. Chlorurus spilurus: comparisons of growth between MPAs for all of Guam (C), western Guam (D), southern Guam (E), and in American Samoa (F). Lethrinus harak: comparisons of growth between MPAs for all of Guam (G) and MPA comparisons corrected for habitat (H).

A second concern with a strong influence on life-history trait values is the varying application of the von Bertalanffy growth formula (VBGF). Two issues stem from this in particular: (1) even in the best data conditions, the VBGF does not provide a perfect fit for all fish species; and (2) under most data conditions associated with fisheries dependent sampling of landings—specifically, inadequate sampling of the youngest and smallest classes—scientists often choose to constrain their growth curve to biologically-realistic settlement sizes (i.e., constraining the y-intercept). Alternatively, growth curves can be fitted using an unconstrained process that fits the observed length-at-age data better, but may misrepresent the early growth trajectory of the youngest individuals. These two approaches, constrained versus unconstrained, can generate significantly different fits and growth parameter values (Figure 2). The constrained option will often reflect growth of the population most holistically across the full life span; however, for many species, constraining the curve to small (but biologically-realistic) settlement sizes will force an earlier, and therefore smaller, asymptote in the growth pattern (Figure 2). The second option of not constraining the settlement size will generally provide a better fit through the raw size-at-age data points, at the expense of providing a biologically-unrealistic early growth trajectory. **However, because early life stages are largely absent from fisheries catch data, and inaccurate information across this stage will generally have a very minimal influence on fisheries models, we recommend the use of unconstrained growth parameters for fisheries assessments conducted in this report.** Note we have opted against the data-poor technique of stepwise meta-analytical imputation in cases where local data exists as this has been found to overestimate growth and maturation trait values by up to 40%.

We last discuss spawning potential ratios (SPR) for small-bodied, fast growing species of reef fishes. For several species fitting this description, we found that using L_∞ obtained from empirical life-history data always resulted in SPR outcomes of 1, implying that no fishing pressure existed for these species. This is obviously unrealistic given that local fishery-dependent surveys have recorded harvest of these species for decades. These species, however, exhibit an inherent rapid growth to a strong asymptote in size-at-age profiles, and generally have considerable variation around their estimated L_∞; i.e., the oldest individuals can occupy a wide range of body lengths. For this reason, the analytical process behind SPR calculation contains high uncertainty in attempting to predict natural length frequency distributions from highly variable and asymptotic growth profiles. Therefore, the size-based outcomes are often indistinguishable between observed fished populations and simulated unfished populations despite their being age truncation within the fished population. Hence, to provide an alternative precautionary approach for these species, we also modelled SPR based on L_∞ values set to the 90th percentile of the observed length-frequency data from the fishery. This size threshold was observed to be consistent with L_∞ values in larger-bodied, slower growing species in the fishery.

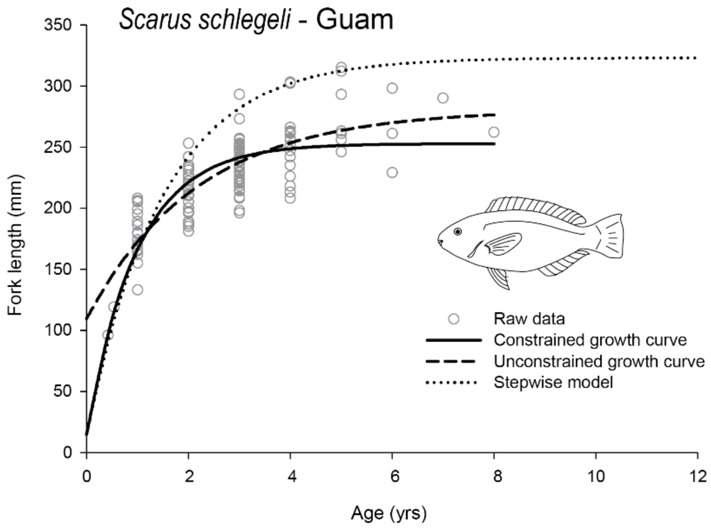

Figure 2. Different approaches to fitting growth curve parameters to raw data for Scarus schlegeli from Guam. Solid line represents a von Bertalnffy growth function (VBGF) model fit to data by constraining the size at settlement to a biologically-realistic estimate. Dashed line represents the same model without constraints. Dotted line represents a fitting of parameter values from the stepwise meta-analytic simulated approach based on size distribution data from NOAA diver surveys and Guam creel surveys (Ahrens & Nadon 2023).

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