Guam JCR-FMP: PIFSC ESD analysis

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Executive Summary

This report details the results of a series of analyses conducted by PIFSC staff to support the development of the Guam Jurisdictional Coral Reef Fisheries Management Plan (JCR-FMP). These analyses examine (1) the status and trends in population size structure of jurisdiction-specific priority species as provided by the Pacific Islands Regional Office (PIRO) Habitat Conservation Division (HCD) and (2) herbivore fish biomass and diversity.

We compiled size distributions for each priority species across the jurisdiction. We found reduced mean size of reef fish in Guam over time, along with corresponding reductions in the biomass of the largest size classes. Furthermore, we observed truncated size distributions in the inhabited islands compared to the uninhabited islands of the archipelago, and these differences between inhabited and uninhabited islands increased over time. Taken together, these findings suggest the potential for intact size distributions of the priority species in Guam to be restored to increase population productivity.

Among herbivore indicators, we found that mean herbivore biomass was significantly lower in Guam compared with the uninhabited islands of the archipelago. We further observed a decline in herbivore biomass over time in Guam. Herbivore species richness was lower in Guam compared with the remaining islands. The temporal decline in the reef ‘excavators’ functional group was particularly noteworthy. Lastly, we observed wide variation in herbivore biomass among sub-island reporting sectors, with high herbivore biomass at Pati Point and Tumon Bay.

While direct assessment of population productivity is beyond the scope of the report, we found indications that Guam’s reef-fish populations have experienced a substantial decline relative to uninhabited islands in the Mariana Islands archipelago. This finding serves as a baseline to compare the effects of future management efforts. It highlights an opportunity to improve these indicators towards enhancing the population productivity of the priority species in Guam.

Introduction

This report details the results of a series of analyses conducted by the staff of NOAA Pacific Islands Fisheries Science Center (PIFSC), Ecosystem Science Division (ESD) to support the development of Jurisdictional Coral Reef Fisheries Management Plans (JCR-FMPs) in the U.S. Pacific Territories. The JCR-FMPs represent comprehensive resource management plans for each territory, focusing on coral reef fishery resources in territorial waters (0-3 nautical miles from shore). These plans are being developed by the territorial resources management agencies, in collaboration with local partners and stakeholders, with support from NOAA Pacific Islands Regional Office (PIRO) and other federal partners.

The overarching goals of the JCR-FMPs are to ensure sustainable nearshore coral reef fisheries in the territories, prevent overfishing, restore overfished species, and protect critical coral reef habitats. Specific targets have been identified to ensure sustainable fisheries of priority species (Table 1):

- Protect 20% of adult females
- Protect 30% of cumulative spawning potential

Various management options (e.g., bag limits, size limits, seasonal closures) were identified by Guam as potential tools for achieving these sustainable fisheries targets. Evaluating these proposed management controls in terms of their ability to achieve the targets for priority species is a key step in developing effective JCR-FMPs. While direct evaluation of potential management options is beyond the scope of this report, analyses of existing long-term fisheries-independent data from the National Coral Reef Monitoring Program (NCRMP), formerly known as the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP), was identified as an important foundational step by providing critical baseline summaries of target populations and identify potential sensitive and relevant indicators of population productivity. The analyses include two broad sections:

- Status and trends in population size structure and size-related indicators toward biological targets for the jurisdiction-specific priority species
- Analysis of herbivore fish biomass and diversity towards ecological indicators of coral-reef habitat quality

How these analyses support the development of the JCR-FMPs

Size structure

The analysis of population size structure using existing fisheries-independent data from the NCRMP will clarify the present conditions of priority species, an important first step toward evaluating management controls using biological targets. Stock assessment and productivity models that can be used to evaluate management actions (e.g., size limits, bag limits) and their effects on cumulative reproductive potential require baseline population size distributions as an important input. Nadon (2019) states that size structure and abundance data from fisheries-independent diver surveys are used for spawning-potential ratio (SPR) calculations (a major proposed biological target), and abundance data are used to derive total population biomass estimates for select species.

Further value of this analysis will be establishing a baseline for these important fishery parameters against which to measure possible future changes and, through monitoring, determine how well management actions are working and adapt accordingly (i.e., adaptive management).

Herbivore biomass and diversity

Complex and "healthy" coral reef habitat is essential to maintaining the full carrying capacity of fish populations that support and maximize the sustainability of directed fisheries on priority species. Herbivorous fish are particularly important in maintaining quality habitat, as they forage on algae that can compete for habitat space and limit the recruitment and growth of corals and, consequently, reef fish. Expansive algal growth also contributes to reef degradation, resulting in rubble-type reefs with low rugosity/complexity. This further reduces shelter and habitat space for reef fish and, thus, limits their population sizes. Importantly, overall herbivory rates depend on both total herbivore biomass and the diversity of herbivores due to the complementary nature of various herbivore feeding strategies (Lefcheck et al. 2019).

This project will document the baseline abundance and diversity of herbivorous fishes, providing an important first step toward identifying any potential biomass and diversity thresholds necessary for maintaining healthy coral-reef habitat for healthy reef fish populations. Herbivore information can later be paired with detailed habitat-specific information to further develop thresholds specific to different reef types that occur within each jurisdiction.

Table 1. Priority Species and Species of Special Interest for the Guam JCR-FMP.

Priority Species (initial list)		Species of Special Interest
Acanthurus guttatus	*Lethrinus harak*	***Bolbometopon muricatum***
Acanthurus lineatus	***Lethrinus olivaceus***	***Cheilinus undulatus***
Acanthurus triostegus	*Lethrinus obsoletus*	*Plectropomus laevis*
Caranx ignobilis	*Lethrinus xanthochilus*	
Caranx melampygus	*Lutjanus fulvus*	
Cheilinus fasciatus	*Mulloidichthys flavolineatus*	
Chlorurus frontalis	*Parupeneus barberinus*	
Chlorurus spilurus (C. sordidus)		
Ellochelon vaigiensis	*Scarus psittacus*	
Epinephelus hexagonatus	***Scarus schlegeli***	
Epinephelus merra	*Siganus argenteus*	
Gerres oyena	*Siganus spinus*	
Hipposcarus longiceps		
Kyphosus cinerascens		

Identified species were provided by the PIRO Habitat Conservation Division (HCD) and further refined through time with input from the jurisdiction. Species names in bold indicate species included in the most recent list of JCR-FMP priority species when the analyses in this report were conducted (Summer 2022).

Questions that this report addresses

Size structure of priority species

- What is the overall characterization of species size distribution across Guam and the Commonwealth of the Northern Mariana Islands (CNMI) for the priority species?
- Are there important differences that should be considered between species and their size distributions at various survey depth strata?
- Does the size structure for priority species differ among islands, especially with respect to varying harvest levels (to the degree known)? Is there variability over the Mariana Islands archipelago (higher populated vs. sparsely populated)?
- Has the size structure for any of the priority species changed over time?
- Are there any direct management considerations (i.e., biomass change without size-structure change or vice versa)?

Herbivore biomass and diversity

- What is the overall spatial distribution of herbivore fish biomass, in terms of density and diversity in Guam and the CNMI?
- Does herbivore fish biomass and diversity differ among islands? Is there variability across the Mariana Islands archipelago (higher populated vs. sparsely populated)?
- Has herbivore fish biomass and diversity changed over time? Can any such changes be correlated with the timing of management interventions if effectively enforced?
- Are there any "red-flag" areas that herbivore biomass indicators can inform at the sub-island scale?

Methods

Data collection

This analysis employs data from the NOAA National Coral Reef Monitoring Program (NCRMP) in the Mariana Islands archipelago, formerly known as the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP), conducted by NOAA PIFSC ESD. Specifically, surveys from 1043 forereef sites (≤ 30 m depth) were compiled for Guam and the Commonwealth of the Northern Mariana Islands (CNMI) for archipelago-wide comparisons.

While RAMP surveys have been conducted across the U.S. Pacific Territories since 2000, the survey design and monitoring methods were not standardized by national NCRMP protocols until 2010. Thus, we have restricted our analyses to surveys conducted in Guam and the CNMI from 2011 onward. Before 2010, the Pacific RAMP used different survey methods and statistical sampling design to assess fish populations, preventing the integration of data in an appropriate and rigorous manner. Note that although NCRMP surveys in Guam and CNMI were completed as part of the recent NOAA Rainier Integrates Charting, Hydrography, and Reef Demographics (RICHARD) cruise in 2022, data from these surveys were not available at the time of initial writing. Surveys were typically conducted in the spring through early-summer months (end of March through mid-June), except a few additional surveys in 2014 that were also conducted in October. Agrihan was not surveyed in 2014.

Survey design

For NCRMP data, site selection and subsequent data pooling are hierarchical, using a stratified random design (StR) to ensure that reefs are surveyed as widely as possible to cover large areas in an unbiased manner. This goal is achieved by splitting the total area of hard-bottom habitat in each island (or sub-island sector for larger islands) into ‘strata’ based on depth (shallow = >0 – 6 m; mid= 6 – 18 m; deep = 18 – 30 m) and by reef zone (backreef, forereef, lagoon, protected slope). The target number of sites per stratum is determined by proportionally allocating total expected sites based on a weighting factor calculated from the size of the strata and the variance of the target output metrics (e.g., consumer group biomass and total fish biomass).

Summary statistics (e.g., mean and variances) of survey quantities (e.g., biomass) were calculated from the surveys within each stratum. To pool those up into larger units (e.g., island), we weighted each stratum by its relative size (i.e., if a stratum is 50% of the total area for each reporting unit [typically island or atoll] then the weighting factor will be 0.5, and a total of all weighting factors sums to 1. Per-strata mean and variance values were aggregated to a higher level (e.g., to island scale) using the formulas found in Heenan et al. (2017).

Reef-fish survey methods

The number and size of all observable reef fishes (limited mainly to diurnal and non-cryptic species) were estimated using stationary point count (SPC) surveys. At each site, divers conducted simultaneous visual fish counts in two adjacent visually-estimated 15-m diameter cylindrical plots that extend from the seafloor to the surface or the limit of vertical visibility. Depending on site-specific constraints (e.g., limited visibility), between one and occasionally up to four cylinders were employed. In the first 5-min period, divers compiled lists of all species observed within the survey, then counted and estimated the size (total length [TL] to the nearest cm) of listed species present within the cylinder over approximately 30 minutes. Heenan et al. (2017) provides full details on SPC survey methods.

Calculating fish biomass

Using the count and size estimate data collected per diver in each replicate cylinder survey, the body weight of individual fish was calculated using length-to-weight (LW) conversion parameters (total and fork length conversions as appropriate). Site-level estimates of abundance and biomass were calculated by taking the mean of the values from the adjacent diver-level counts conducted for each survey.

Analysis

Size structure of priority species

The overall goals for this section of the analysis were to (1) clarify present conditions (i.e. population size structure) of priority species toward evaluation of management controls using biological targets and (2) establish a baseline for these important size metrics upon which to measure possible future changes through monitoring.

To address these goals, for each of the priority species identified (n = 30), every observation of the species during the focal research period was compiled. These data were then analyzed at various spatial (i.e., island and archipelago) and temporal scales to calculate mean TL, maximum TL, and size quantiles. The size distribution of each species was visualized as both biomass within discrete size bins and continuous size distributions from individual observations. Summaries of these metrics were compiled for each species to evaluate size metrics for:

- jurisdictional populations
- island-scale populations
- groups of islands (higher populated vs. sparsely populated)
- changes over time

Herbivore biomass and diversity

The overall goals of this section of the analysis were to (1) document the current baseline abundance and diversity of herbivorous fish toward identifying thresholds for maintaining healthy coral-reef habitat and (2) identify any “red flag” areas where herbivore biomass appears to be particularly low.

Using the statistical pooling methods described above, the overall herbivore biomass, biomass within functional group, and herbivore species diversity were compiled at the following scales:

- jurisdiction-wide
- per island
- per group of islands (higher populated vs. sparsely populated)

In addition, each metric (at each scale) was summarized per year to evaluate changes through time that may correspond to prior management interventions. Herbivores were subdivided into functional groups following standard NCRMP reporting categories. These include the following categories: grazer, scraper, browser, excavator, and detritivore. The definitions for each of these functional groups are shown in Table 2.

Table 2. Herbivore functional groups.

Functional group	Feeding mode description	Example from jurisdiction
Browsers	Feed on fleshy and upright macroalgae and associated epiphytic material	*Naso lituratus** (Orangespine unicornfish)
Grazers	Feed intensely on epilithic algal turf (and associated detritus) without removing reef substratum	*Acanthurus lineatus** (Lined surgeonfish)
Scrapers	Consume epilithic algal turf (and associated detritus) and remove *small* portions of the reef substratum	*Scarus schlegeli** (Yellowband parrotfish)
Excavators	Feed on epilithic algal turf (and associated detritus), removing *substantial* amounts of the reef substratum	*Chlorurus frontalis** (Tan-faced parrotfish)
Detritivores	Feed primarily on detritus but may occasionally consume turf algae	*Ctenochaetus cyanocheilus* (Bluelip bristletooth)

Description of herbivore functional groups' feeding modes with an example from the jurisdiction. An asterisk (*) indicates species that PIRO-HCD identified as a priority species for the Guam JCR-FMP at the time when the analyses in this report were conducted (Summer 2022). Epilithic algal turf refers to low-lying algae that grow on hard substrata.

Results

We compiled size distributions for each of the priority species in Guam from 21,662 total observations across the jurisdiction over the survey period. Among priority species, the mean total length (TL) ranged from 10.9 cm for *Acanthurus triostegus* to 82.0 cm for *Caranx ignobilis*. Across all priority species, mean TL was highest in 2011 (17.9 cm) and 2014 (18.3 cm), with indications of a decline in population size structure across the aggregate species pool by 2017 (17.3 cm).

Size structure among priority species

Question S1: What is the overall characterization of species size distribution across Guam and the CNMI for the priority species?

We observed only modest differences in size indicators when comparing the size distributions within species aggregated across all 3 survey years (2011, 2014, and 2017) between Guam and the remainder of the Mariana Islands archipelago (including CNMI; Table 3). This result should be interpreted with caution, however, for at least two reasons. Subsequent analyses (grouping Guam with the other inhabited islands) showed more substantial discrepancies in the size structure of priority species (see Question 3 below). Furthermore, differences in size indicators between Guam and the CNMI – in aggregate and within individual species – increased over the survey period between 2011 and 2017.

For most of the priority species at the jurisdictional scale, large sample sizes provided relatively precise estimates of size indicators (i.e., narrow distributions in Figure 1), except for *Cheilinus undulatus,* which was not frequently observed. Therefore, these data provide a reasonably sensitive baseline from which to compare responses to future management interventions.

Table 3. Mean total length of 10 priority species, comparing Guam with the broader Mariana Islands archipelago.

Species	Mean total length (cm)	
	Guam	archipelago-wide
Acanthurus lineatus	16.4	16.7
Naso lituratus	15.8	18.3
Caranx melampygus	31.3	34.5
Kyphosus cinerascens	NA*	33.8
Cheilinus undulatus	50.4	49.0
Lethrinus olivaceus	44.5	39.5
Lutjanus fulvus	20.6	21.3
Chlorurus frontalis	23.7	25.1
Scarus schlegeli	20.9	20.8
Epinephelus merra	16.9	18.1

*Note: There were no observations of *Kyphosus cinerascens* in Guam during the observation period.

One important caveat to the interpretation of population size structure from these data is that both NCRMP site selection (limited to hard-bottom habitats) and the SPC methodology bias the data toward capturing adults and larger individuals over juveniles, especially for species that undergo habitat shifts across their post-settlement life cycle (e.g., where juveniles occupy mangrove or seagrass habitats). Therefore, comparing these size distributions to data collected by other means is not advised.

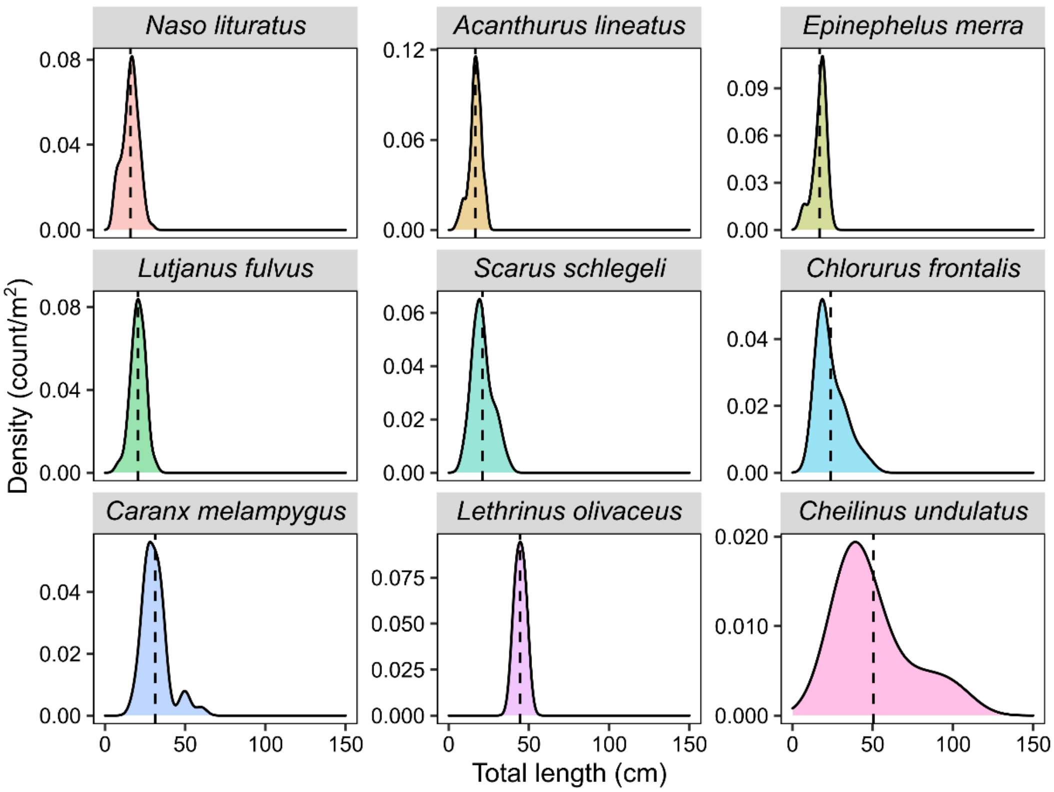

Figure 1. Size distributions of each of the final priority species for Guam.

Dashed vertical lines indicate the mean TL per species. Note that the scales of y-axes differ among plots.

Question S2: Are there important differences that should be considered between species and their size distributions at various survey depth strata?

Several priority species showed clear depth-specific differences in size metrics. For example, *Acanthurus lineatus* and *Chlorurus frontalis* showed major differences in mean TL and the overall distribution of large individuals (Figure 2). In both cases, the deeper sites showed substantially higher mean sizes compared to moderate or shallow sites.

However, differences in distributional patterns for these two species may indicate that these depth-specific size differences originate from different mechanisms (Figure 2). In the case of *Acanthurus lineatus*, large individuals occur across depths, and differences in mean TL appear to result from juveniles preferentially occupying shallow habitats. In contrast, the largest individuals of *Chlorurus frontalis* are only rarely observed outside of deep habitats, potentially indicating a depth refuge for this species.

Regardless of the mechanism, the strong signal of depth in several priority species indicates that this factor is a critical consideration for setting and measuring progress toward any size-based conservation targets and identifying appropriate management interventions.

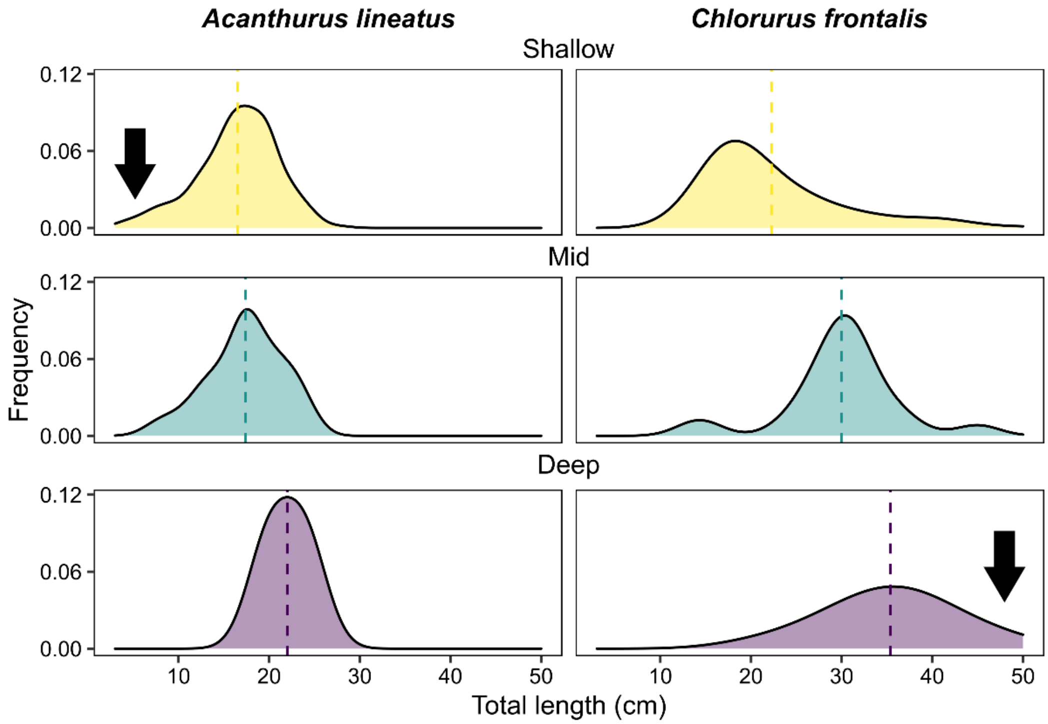

Figure 2. Depth-specific size distributions for two example priority species. Arrows indicate sizes that appear to drive the variance in distribution and mean total length across depths.

Dashed vertical lines indicate the mean TL per species.

Question S3: Does the size structure for priority species differ among islands? Is there variability over the Mariana Islands archipelago (higher populated vs. sparsely populated)?

There are clear island-specific differences in size indicators, particularly when comparing populated vs. unpopulated islands in the Mariana Islands archipelago. This is true both in aggregate and within specific individual species.

Aggregated across priority species, the mean TL at each populated island is lower than that of every unpopulated island, except Aguijian (Figure 3). Ranking islands by aggregate size metrics, Guam ranks 7th overall out of the 10 islands assessed and 2nd highest among populated islands. Similarly, comparing size indicators between populated and unpopulated islands within individual species indicates substantial differences in mean, maximum, and where the bulk of the size-frequency distribution lies.

Taking two examples, *Chlorurus frontalis* and *Lethrinus obsoletus* at unpopulated islands have a substantially higher mean and max TL than at populated islands (Figure 4). In contrast, species such as *Lutjanus fulvus* show no such disparities. While the relative intensity of fishing among priority species was not included in this analysis, linking fishing pressure to size disparities among islands merits future investigation. Nevertheless, it is apparent that at least some of the priority species show a truncated size distribution at islands with human inhabitants, with implications for population productivity (see Discussion).

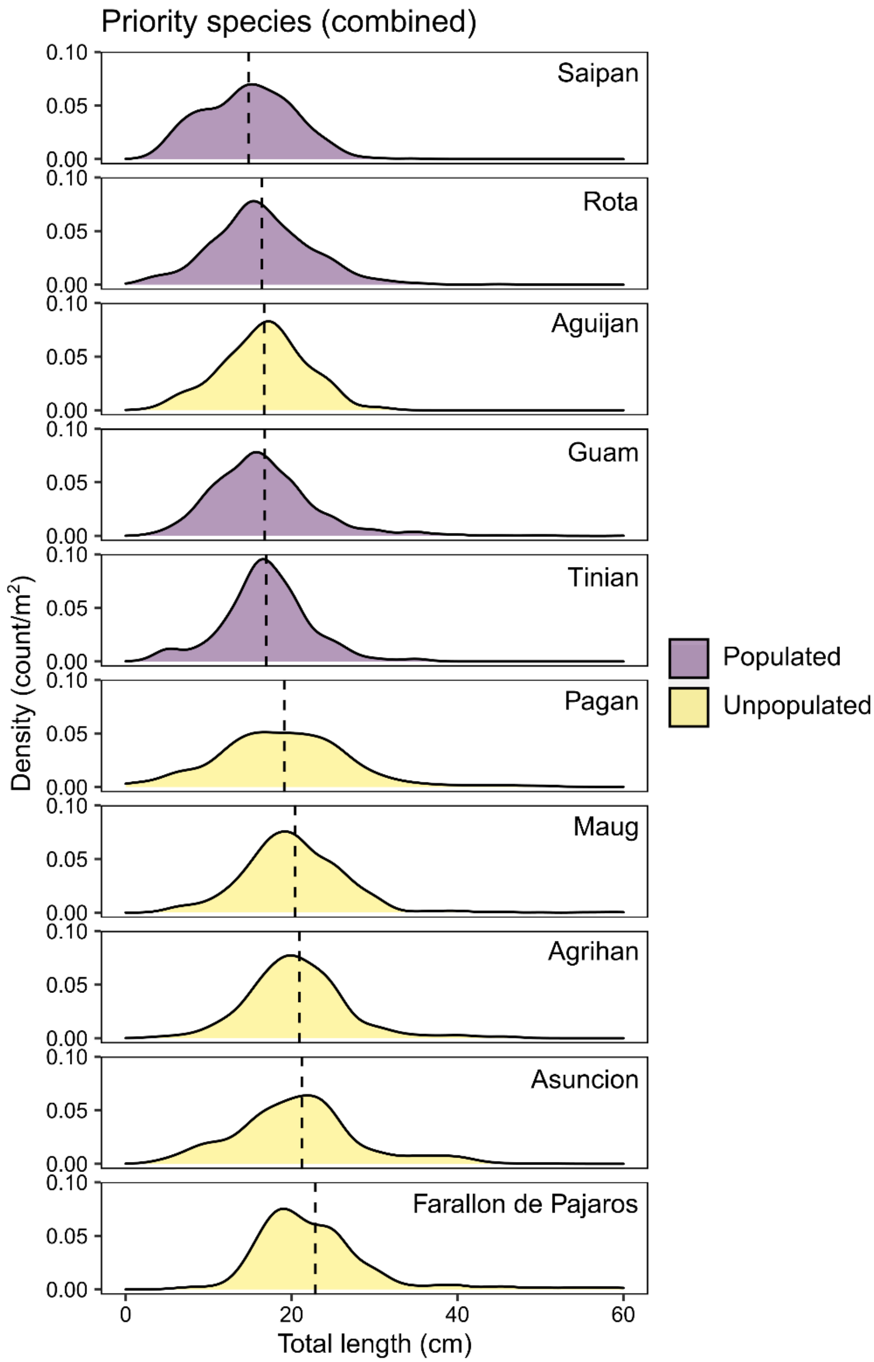

Figure 3. Aggregate size distribution for all priority species combined by island.

Populated islands are in purple and unpopulated islands are in yellow. Dashed vertical lines indicate the mean TL.

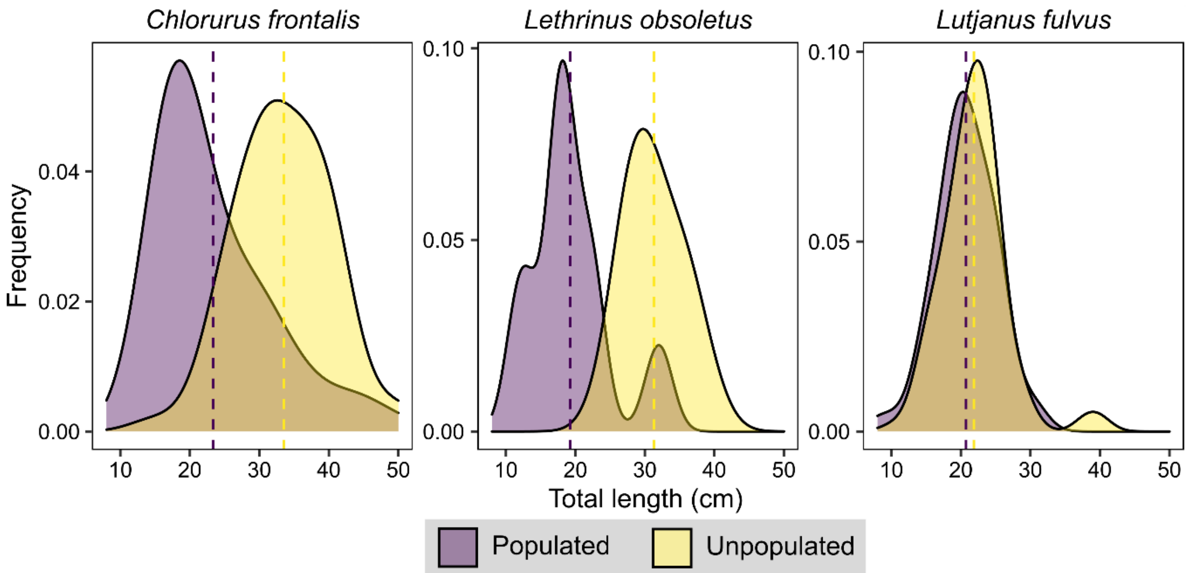

Figure 4. Size distribution for three priority species at populated and unpopulated islands.

Populated islands are in purple and unpopulated islands are in yellow. Dashed vertical lines indicate the mean TL. Note that the scales of y-axes differ between plots.

Question S4: Has the size structure of any of the priority species changed over time?

Aggregating across all priority species, there is weak evidence of size decreases through time in Guam and no indication of declines in size metrics across the broader archipelago. In contrast, individual species show differences in size distribution over time, with truncated size distributions in 2017 compared with earlier data (2011 and 2014).

For example, *Acanthurus lineatus* shows a decline in both mean TL and in the biomass of individuals larger than 20 cm TL (Figure 5). Although the overall biomass of the species declined between 2011 and 2017, the biomass of small individuals remained roughly the same. In contrast, the biomass represented by individuals >15 cm and especially those >20 cm showed dramatic declines. As larger individuals provide major contributions to population productivity, this decline in proportional biomass represented by large individuals is notable.

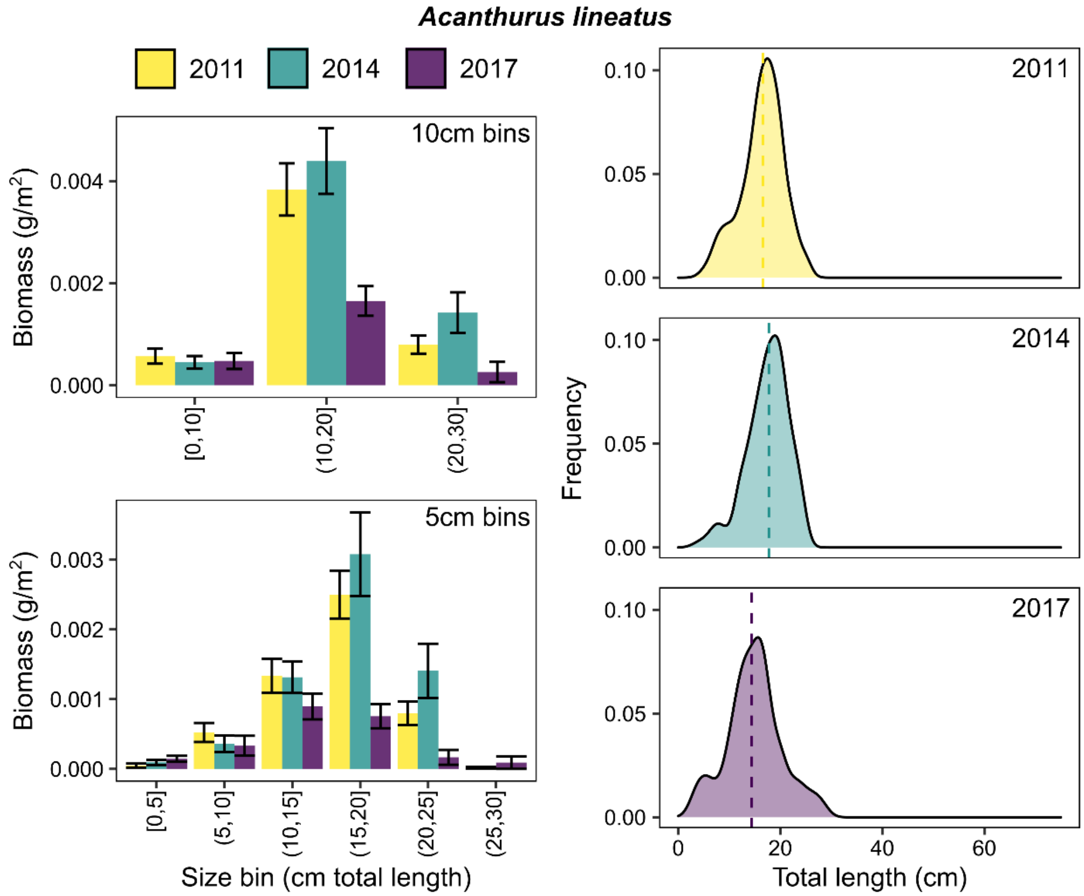

Figure 5. Size distribution through time for a priority species.

Dashed vertical lines indicate the mean TL. Error bars are the standard error of the mean (SEM). Note that the scales of y-axes differ among plots.

Question S5: Are there any direct management considerations (i.e., biomass change without size-structure change or vice-versa)?

While many of the priority species showed a decline in mean TL, we also observed species whose average size remained relatively stable over time, but nevertheless showed important changes in other indicators. It is important to note that mean TL captures only a single dimension of population health and productivity assessment.

For example, the size distribution of *Lutjanus fulvus* remained largely unchanged from 2011 to 2017 (Figure 6). However, this masked (1) an overall decline in biomass in every 5cm size bin from 2014 to 2017 (i.e., an overall decline in biomass) and (2) the absence of any observations in > 20 cm TL size bins. This result underlines the importance of assessing the effects of management interventions on the health and productivity of priority populations using a diversity of metrics that include, but are not limited to, population size indicators.

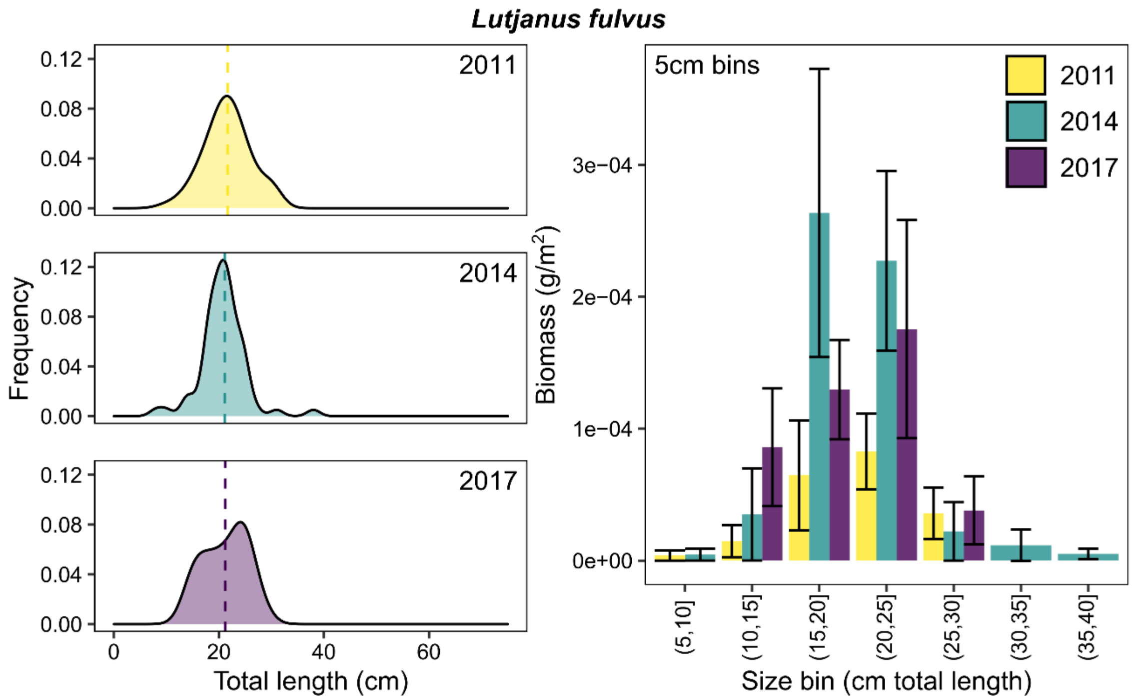

Figure 6. Change in biomass without corresponding changes in size indicators.

Dashed vertical lines indicate the mean TL. Error bars are the standard error of the mean (SEM).

Herbivore biomass and diversity

Question H1: What is the overall spatial distribution of herbivore fish biomass, in terms of density and diversity in Guam and the CNMI?

Across the Mariana Islands archipelago, mean herbivore biomass (averaged across years) ranged from less than 4 g/m^2 at Saipan and Tinian to over 7 g/m^2 at Agrihan (Table 4). Guam ranked 3rd lowest among the islands in terms of overall herbivore biomass with 4.8 g/m^2.

Overall, herbivore biomass was not distributed evenly among functional groups, with grazers representing the highest proportion of individuals and biomass in Guam and archipelago-wide (Figure 7). In the Marianas, this group was followed by detritivores, scrapers, and excavators with roughly similar overall biomass. In comparison, Guam showed higher levels of scraper biomass, similar levels of detritivore biomass, and reduced levels of excavator biomass (particularly in later years; see Question 3 below) compared with the archipelago as a whole.

Due to their importance in bioerosion and clearing substrate for settlement habitat for coral recruits, this reduction in the biomass of large excavators in Guam has important implications for the health of coral habitats in Guam.

Table 4. Mean herbivore biomass by island.

Island	Mean herbivore biomass (g/m^2)
Tinian	3.7
Saipan	3.9
Guam	4.8
Rota	5.2
Farallon de Pajaros	5.5
Aguijian	5.6
Maug	7.7
Asuncion	8.2
Pagan	8.5
Agrihan	10.7

Mean total herbivore biomass averaged across observation years. Islands are ordered (top to bottom) from lowest to highest mean total biomass.

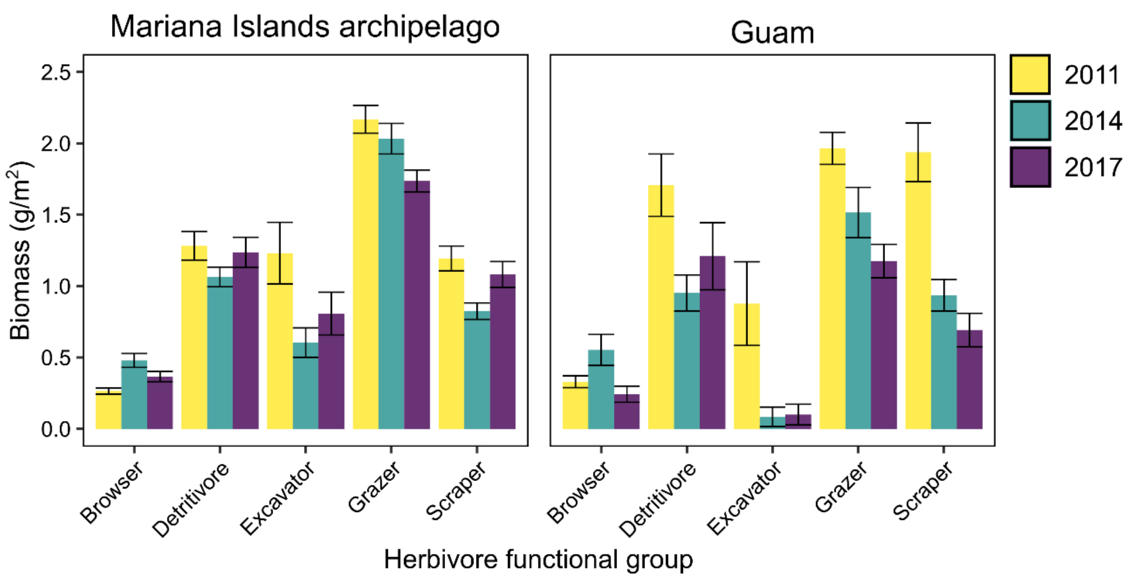

Figure 7. Biomass per herbivore functional group through time in the Mariana Islands archipelago and Guam.

Error bars are the standard error of the mean (SEM).

Question H2: Does herbivore fish biomass and diversity differ among islands? Is there variability across the Mariana Islands archipelago (higher populated vs. sparsely populated)?

There were clear differences in herbivore biomass, abundance (density), and to a lesser extent, species richness among islands, particularly in comparing populated versus unpopulated islands (Figure 8).

While we observed inter-island variability, herbivore biomass was greater at unpopulated islands, and this distinction remained consistent throughout the survey period. Herbivore density (the number of individuals per unit area) was also higher at unpopulated islands, but unlike biomass, this discrepancy increased over time. Finally, species richness – a less sensitive signal of differences in community differences – showed more modest differences among islands, with a less pronounced difference between populated and unpopulated islands.

Taken together, these results reveal important differences in the state of herbivore populations across the archipelago and highlight an opportunity to improve the condition of herbivore populations in Guam towards maintaining healthy coral-reef habitat for reef fish populations.

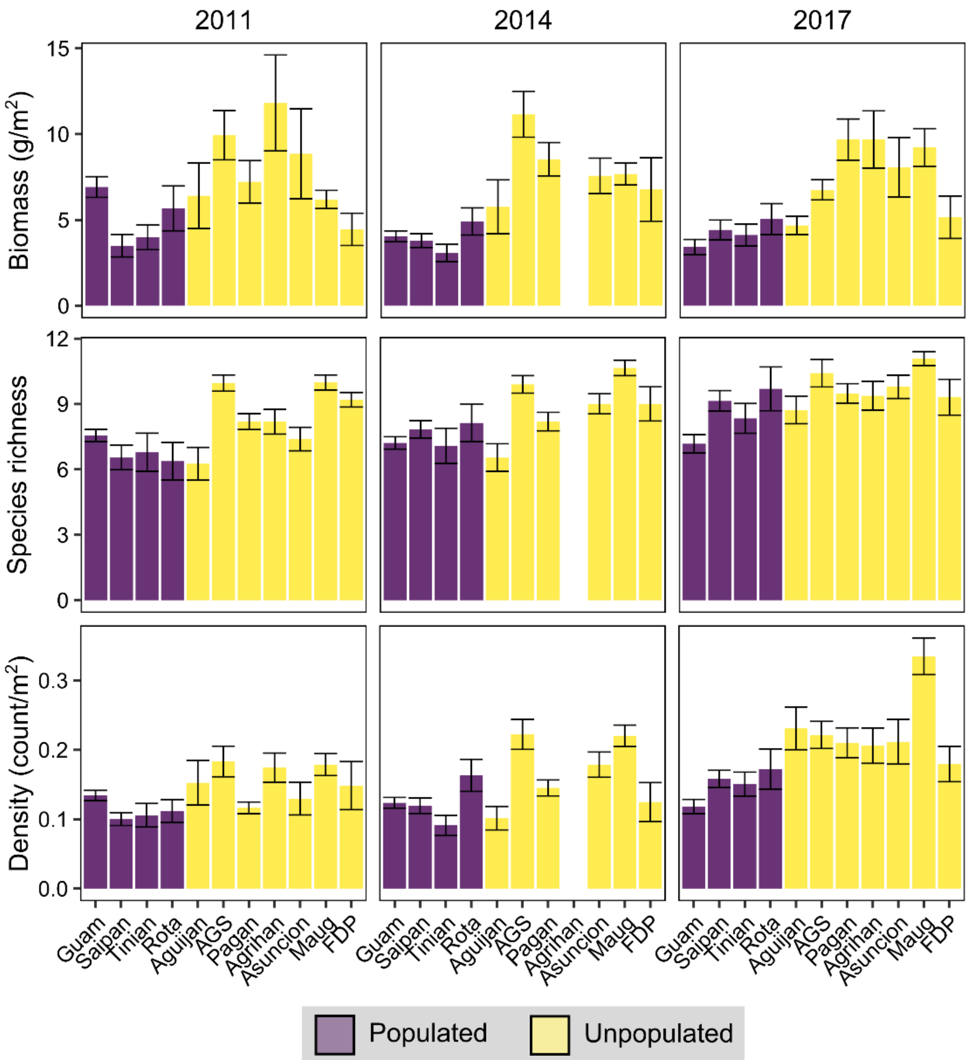

Figure 8. Herbivore biomass, diversity (species richness), and density per island through time.

Populated islands are in purple and unpopulated islands are in yellow. 'FDP' is Farallon de Pajaros, and 'AGS' is a combined survey unit consisting of Alamagan, Guguan, and Sarigan. Error bars are the standard error of the mean (SEM). There were no surveys conducted at Agrihan in 2014.

Question H3: Has herbivore fish biomass and diversity changed over time?

While overall herbivore abundance (density) and species richness have been relatively stable over time, the biomass of herbivorous fishes in Guam declined precipitously between 2011 and 2014, and further in 2017 (Figure 9). By contrast, this same decline in biomass was not observed archipelago-wide, with most islands showing similar levels of herbivore biomass throughout the survey period (Figure 10).

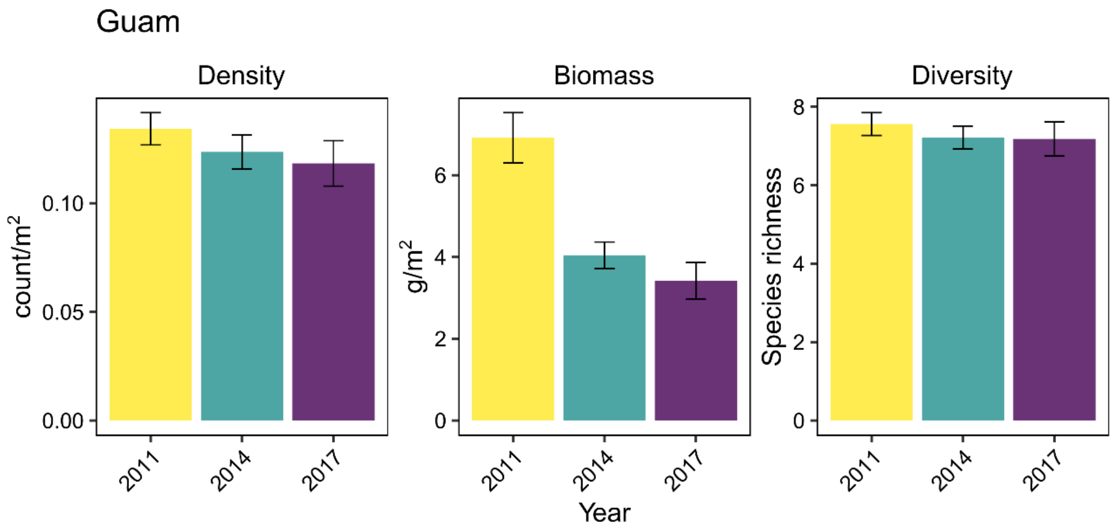

Figure 9. Herbivore density, biomass, and species richness in Guam through time.

Error bars are the standard error of the mean (SEM).

This decline in herbivore biomass in Guam occurred across functional groups, with the lowest biomass for every functional group occurring in 2017 (Figure 7). However, the decline in excavators was most pronounced, with a precipitous decline in this important group between 2011 and 2014 (remaining similarly low in 2017).

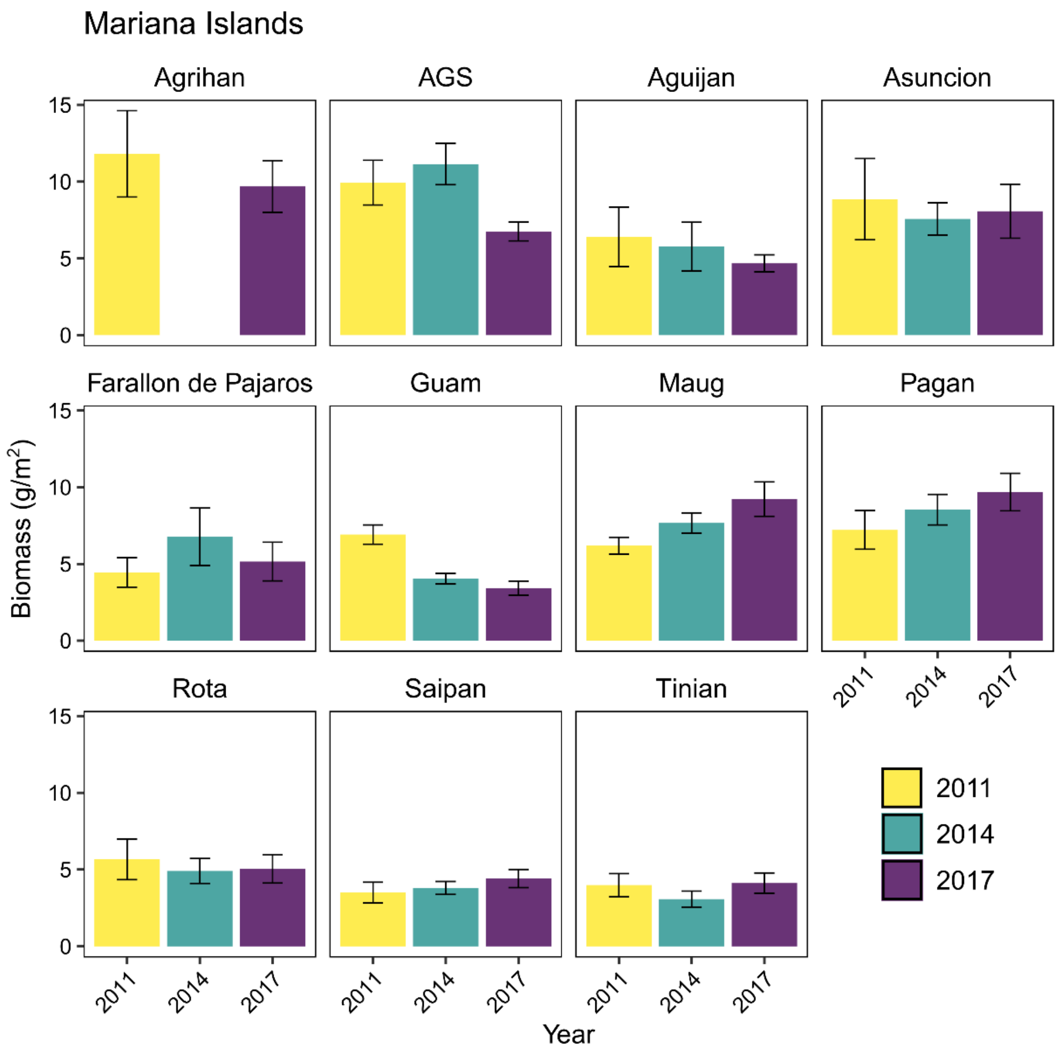

Figure 10. Herbivore biomass at each island through time.

'AGS' is a combined survey unit consisting of Alamagan, Guguan, and Sarigan. Error bars are the standard error of the mean (SEM).

Question H4: Are there any 'red-flag' areas in herbivore biomass indicators?

At the island scale, the populated islands, particularly Guam, Saipan, and Tinian, clearly show reduced herbivore biomass compared to islands with fewer human impacts (Figure 8).

Within Guam, herbivore biomass is highest in the sector near Pati Point (24.9 g/m^2) and Tumon Bay (22.6 g/m^2) and lowest in West (5.5 g/m^2) and North (7.6 g/m^2) with the remaining sectors roughly equal at approximately 10 g/m2 (Figure 11).

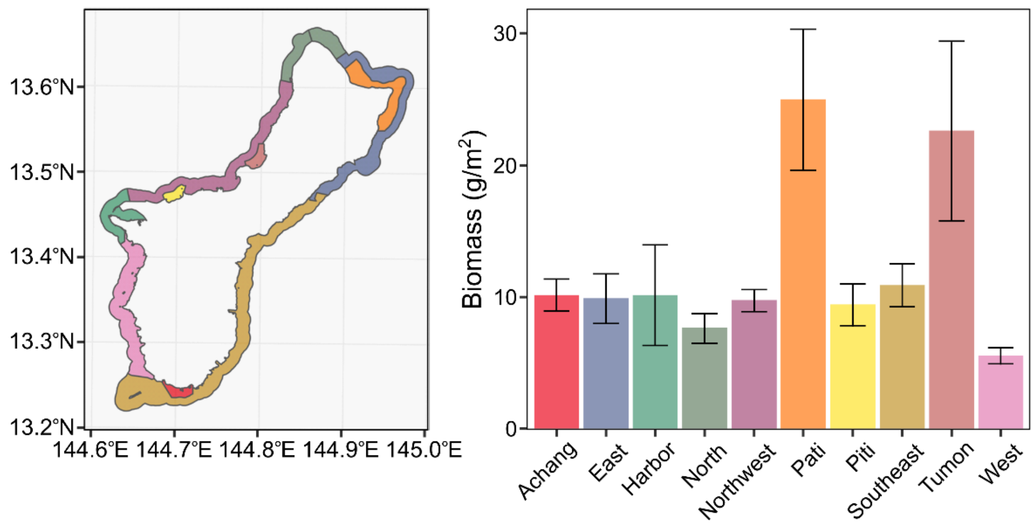

Figure 11. Herbivore biomass at Guam by sub-island sector.

Color-coding of sectors is consistent between the map (left) and barplot (right). Error bars are the standard error of the mean (SEM).

Discussion

This assessment focused on two primary categories of reef-fish indicators (priority-species size structure and herbivore biomass and diversity) as foundational steps toward evaluating the impact of management interventions on population productivity and habitat quality. While direct assessment of population productivity is beyond the scope of this report, we found evidence (in both sets of indicators) that Guam's reef-fish populations have experienced a substantial decline relative to uninhabited islands in the Mariana Islands archipelago. This finding represents an opportunity to compare the effects of future management efforts in Guam to the current baseline, with the corresponding changes in reef-fish indicators at the uninhabited islands serving as temporal controls.

In the first category (size metrics), we found reduced mean size of reef fish in Guam through time—in aggregate and within individual species—and corresponding reductions in the biomass of the largest size classes. Furthermore, we observed truncated size distributions (i.e., missing the largest individuals) at the inhabited islands compared to the uninhabited islands of the archipelago, and these differences between inhabited and uninhabited islands increased through time. Taken together, these findings suggest that restoring intact size distributions of the priority species in Guam may increase population productivity. However, the links between size distribution, population productivity, and particular management controls are not straightforward. While the largest size classes often produce disproportionately more offspring (and higher quality larvae) than smaller mature females across a wide variety of teleost fishes (Hixon et al. 2014), the absolute abundance of medium-sized reproductive individuals mean that intermediate size-classes may be responsible for much of the larval replenishment in many reef-fishes (Lavin et al. 2021).

In the second category, we found that mean herbivore biomass was significantly lower in Guam and the remaining inhabited islands compared with the uninhabited islands of the archipelago. We further observed a decline in herbivore biomass through time in Guam, a temporal trend that was not consistent across the remaining islands. While the relative contribution of herbivore biomass by each functional group was roughly similar between Guam and the broader archipelago, there was a distinct decline in the biomass of 'excavators' in Guam over the survey period. Herbivore species richness was lower in Guam compared with the remaining islands. Lastly, at the sub-island scale at Guam, we observed wide variation in herbivore biomass among sectors, with areas of low herbivore biomass along the southwest coast and in the region around Ritidian Point, and high herbivore biomass at Pati Point and Tumon Bay, which are both areas that are part of Guam's Marine Preserve network.

Herbivore grazing of marine algae serves as a critical ecosystem function that helps improve coral-reef resilience in the face of various stressors (Graham et al. 2013). Thus, closing the observed gap in overall herbivore biomass between Guam and the broader archipelago represents an opportunity to improve habitat for other coral-reef associated fishes indirectly. Importantly, besides biomass, herbivore species richness was also diminished in Guam. Due to the complementarity of herbivore feeding strategies (i.e., targeting different algal growth forms and employing various feeding apparatuses) overall herbivory depends on the diversity of herbivores present as well as their density and size. We found every herbivore functional group exhibited a decreasing trend over time across Guam; particularly notable was the decline in reef 'excavators' such as *Chlorurus frontalis*. These large herbivores are particularly critical due to their importance in bioerosion and in clearing substrate to create settlement habitat for coral recruits (Green and Bellwood 2009).

Two important caveats should be noted here. First, in evaluating the potential for increased herbivore biomass at the island scale, it is important to consider habitat quality as a driver of – and not merely a response to – herbivore population levels. Thus, comparing herbivore biomass and diversity levels among islands may indicate differences in underlying habitat characteristics and the effects of human activities such as fishing. Second, herbivore populations can increase in response to degradation in habitat with corresponding increases in algae (food resource), so high densities of herbivores may not be an indicator of broader ecosystem health.

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