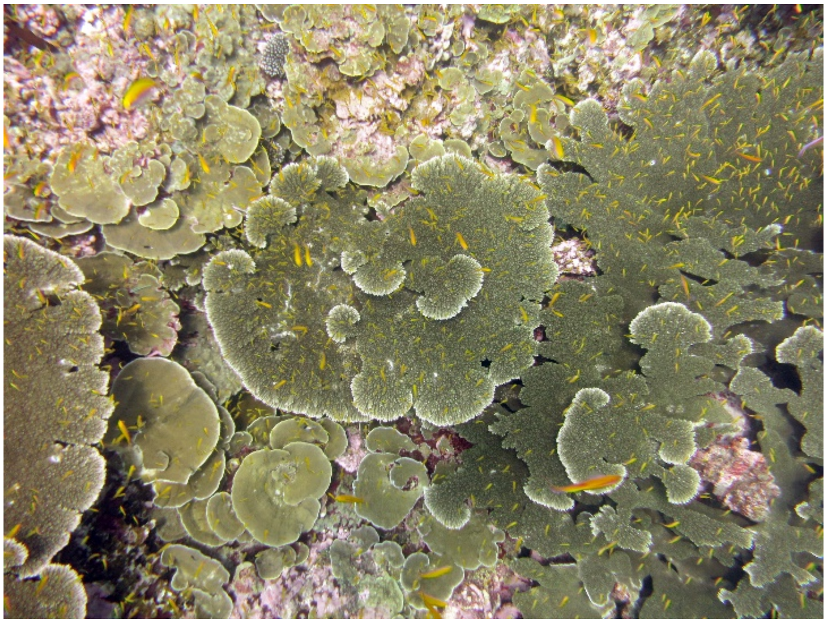
Spatial Prioritization under Resilience-Based Management: Evaluating Trade-offs among Prioritization Strategies

Thomas A. Oliver, Justin Hospital, Russell E. Brainard



U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Pacific Islands Fisheries Science Center

NOAA Technical Memorandum NMFS-PIFSC-105
https://doi.org/10.25923/xdf2-t259

June 2020

Spatial Prioritization under Resilience-Based Management: Evaluating Trade-offs among Prioritization Strategies

Thomas A. Oliver, Justin Hospital, Russell E. Brainard

Pacific Islands Fisheries Science Center
National Marine Fisheries Service
1845 Wasp Boulevard
Honolulu, HI 96818

NOAA Technical Memorandum NMFS-PIFSC-105

June 2020

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Oceanic and Atmospheric Administration
Neil A. Jacobs, Ph.D., Acting NOAA Administrator

National Marine Fisheries Service
Chris Oliver, Assistant Administrator for Fisheries

Recommended citation

Oliver TA, Hospital J, Brainard RE. 2020. Spatial Prioritization under resilience based management: evaluating trade-offs among prioritization strategies. NOAA Technical Memorandum. NOAA-TM-NMFS-PIFSC-105, 47 p. doi:10.25923/xdf2-t259

Copies of this report are available from

Science Operations Division
Pacific Islands Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
1845 Wasp Boulevard, Building #176
Honolulu, Hawaii 96818

Or online at

https://repository.library.noaa.gov/

Cover: Photo credit NOAA PIFSC ESD.

Table of Contents

List of Tables

List of Figures

Executive Summary

Assessing ecological and social resilience to climate change stresses has become a priority in coral reef management worldwide, and there is increasing information on how to best incorporate these assessments into a novel management framework—resilience-based management (RBM). Generally, this body of literature underscores the importance of including resilience assessments in management prioritization, with the explicit strategy of prioritizing action in the areas with highest measured resilience.

However, there is also a diversity of other concerns when prioritizing areas in which to focus management actions. This study considers a total of six commonly cited strategies: a pure resilience focus, prioritizing actions in the areas rated with the ***highest resilience*** to climate stresses; prioritizing actions in areas of ***thermal refugia*** with the least or latest exposure to heat stress; including appropriate ***spatial representation*** by prioritizing areas on each region/island; incorporating as much ***biodiversity*** as possible within the prioritized set; inclusion of living marine resources, specifically ***resource fish biomass***; and placing management in areas of high ***social vulnerability***. Outlined strategies for RBM advocate for different levels of inclusion of each of these issues, but there has been little empirical work evaluating the relative trade-offs of these strategies based on real-world data. By better understanding these trade-offs, we may improve upon a resilience-based strategy that appropriately incorporates these other elements.

Here we empirically evaluate trade-offs among distinct prioritization strategies under RBM to clarify and expand on options managers have for balancing competing prioritizations. First, we report on a climate change vulnerability assessment performed across the U.S. Pacific Islands for both ecological and social variables. Next, we quantitatively assess trade-offs among the six outlined prioritization strategies, using a performance metric for each strategy. After this, we compare trade-offs between a resilience-based prioritization strategy and each of the other five using an efficiency frontier analysis. This analyzes, for example, if we prioritize the sites with the highest resilience ratings does the prioritized set fare poorly in other, reasonable prioritization strategies? Which strategies reinforce each other? Which directly oppose each other? Subsequently we suggest objectives that realistically can be met using blended strategies to better incorporate these empirical trade-offs, as well as other objectives that are mutually exclusive in prioritization of management action.

Thus compared, a resilience-based prioritization performs well for four of the five other objectives, translating into a win-win at some level of prioritization commitment (i.e., reef area under prioritization) for spatial representation, biodiversity, resource fish biomass, and social vulnerability. The clear outlier is in thermal refugia, indicating that those areas with high ecological resilience to thermal stress are not correlated to areas likely to show later thermal exposure. Resource fish biomass also can be a win-win, but only at large commitments to prioritizations (i.e., greater than 30% of reef area prioritized).

Introduction

The Science of Assessing Resilience

While the threat of warming and acidifying seas has been part of the academic discussion for many years now (Hoegh-Guldberg 1998; Kleypas et al. 1999), in the last decade the science of coral reef management has focused on the concept of ecological resilience—taking management action to prioritize and support areas most prone to resist or recover from climate disturbances (Levin and Lubchenco 2008).

A major effort toward this goal is to generate robust metrics which highlight areas that are most likely to be resilient (Obura and Grimsditch 2009; Maynard et al. 2010; McClanahan et al. 2012; Maynard et al. 2012). While some researchers have attempted to ecologically model resilience (Mumby et al. 2014), many resilience metrics generate an aggregate index by quantifying distinct factors, ranging from those prone to support resistance to warming (proportion of bleaching resistant corals, thermal variability), to those prone to support rapid recovery in the face of coral bleaching-related mortality (herbivorous fish biomass, juvenile coral density, etc.) (Obura and Grimsditch 2009; McClanahan et al. 2012). Taken together, using 8−12 factors allows management-focused scientists to quantitatively assess and rank areas from most likely to be ecologically resilient to least likely (e.g., Maynard et al. 2015).

A parallel effort is also under way in the social sciences, working towards the goal of integrating ecological and social perspectives on resilience and vulnerability. This has led to methods and assessments focused on the vulnerability of coastal communities that rely on the marine ecosystem (Jepson and Colburn 2013) or on the social-ecological system as a whole (Cinner et al. 2012).

The Move to Resilience-Based Management

Given quantitative ecological and social metrics of resilience, reef managers have been able to lay out a general strategy to incorporate these metrics in management and conservation planning. This movement has been dubbed resilience-based management (RBM) or adaptive resilience-based management (ARBM) and is supported by a growing body of literature (Anderies et al. 2006; Graham et al. 2013; Mumby et al. 2014; Anthony et al. 2015).

RBM, or ARBM, is generally presented as an extension of existing management frameworks, designed to better incorporate resilience assessment information into standard management practice (Groves et al. 2012; McLeod et al. 2012; Anthony et al. 2015). As part of this framework, managers are asked to set objectives in light of multiple, cumulative stressors, among which anthropogenic warming and acidification loom large (Anthony et al. 2015). Once objectives are established, a broad set of approaches can be employed to operationalize these goals into management actions.

While some proposed management actions may have force throughout a management domain (i.e., fishing size limits), many coral reef management efforts are explicitly spatial (i.e., protected areas). As it is rarely politically or economically viable for managers to apply spatially explicit management everywhere, they must specifically prioritize areas on which to focus.

Spatial Prioritization of Management Effort under RBM

Prioritization strategies under RBM vary with the specific objectives of the management body. That said, a number of themes repeatedly arise in the objective setting phase, and here we consider six distinct strategies. For the sake of considering trade-offs among strategies, we consider the following six "pure" prioritization strategies often cited in discussions of RBM, without constructing a blended approach:

Prioritize *resilience*: A common thread throughout RBM is the incorporation of metrics of ecological resilience in the face of warming and acidification. The contention at the heart of RBM is that we need to include areas of probable resilience to warming in our prioritization. The simplest example of this strategy would be to prioritize areas with the highest resilience metric (Game et al. 2008).

Prioritize *thermal refugia*: One of the earlier strategies proposed for managing in the face of climate change was to focus on areas that would show the least or latest exposure to climate change impacts (West et al. 2003), without reference to the ecosystem response to that warming.

Prioritize *biodiversity*: A major objective of global conservation and management has been to represent the biodiversity of the domain in a set of areas under prioritized management (Roberts et al. 2002; Brooks et al. 2006).

Prioritize *spatial representation*: This strategy focuses on ensuring that all areas and habitats have some place in the protections through broad spatial representation. This approach has been a major part of marine protected area network theory (Crowder and Norse 2008).

Prioritize *resource fish biomass*: If our primary objective is the maintenance of harvestable fish stocks, under this strategy, one would first target areas with a large biomass of these commercially important fishes.

Prioritize *social vulnerability*: Focusing on human populations instead of the ecology, one approach would be to first focus on areas most socially vulnerable to potential disturbances (Jepson and Colburn 2013). While other social prioritization strategies may be reasonable (i.e., prioritizing areas where managers have capacity and influence), selecting this "pure" strategy highlights the trade-offs among socially and ecologically focused strategies.

Trade-offs among Management Priorities

Here we empirically evaluate trade-offs among distinct prioritization strategies under RBM with the goal of clarifying choices managers may make to balance competing prioritizations. We first report on a climate change vulnerability assessment performed across the U.S. Pacific Islands for ecological and social variables. We quantitatively assess trade-offs among the six outlined prioritization strategies, using a performance metric for each strategy. We then compare trade-offs between a resilience-based prioritization strategy and each of the other five using an efficiency frontier analysis. In this analysis we ask, for example, if the sites with the highest resilience ratings are prioritized, do they fare poorly in other, reasonable prioritization strategies? Which strategies reinforce each other? Which directly oppose each other? Then we suggest objectives that likely can be met with blended strategies that may better incorporate these empirical trade-offs, and other objectives that are mutually exclusive in prioritization of management actions.

Methods

We first performed a climate change vulnerability analysis, for both ecological resilience and social vulnerability in the central U.S. Pacific, including all reefs under U.S. federal authority, covering Hawai‘i, the Papāhanaumokuākea Marine National Monument (the Northwestern Hawaiian Islands, NWHI), Guam, the Commonwealth of the Northern Mariana Islands (CNMI), American Samoa, and the remote islands that together make up the Pacific Remote Islands Marine National Monument (PRIMNM). Altogether, this domain covers 59 ecological reef sectors, divided among 5 regions and 37 islands, along with 415 census county divisions (CCDs) in the social analysis (Figure 1).

Ecological Climate Change Vulnerability Analysis

All ecological data were derived from the National Coral Reef Monitoring Program (NCRMP) data sets 2013–2015, with factor selection and calculation following McClanahan et al. (2012) and Maynard et al. (2015). These data were collected during the early phases of a global bleaching event and do not yet include the impacts from that event. This methodology focuses on ecological resilience to the negative impacts of ocean warming and does not meaningfully incorporate exposure or response to ocean acidification. We employed the following eight factors in this analysis, calculated at the sector scale:

- *Bleaching resistant taxa:* The proportion of the coral community resistant to bleaching. This is a sector level combination of the abundance of a given hard coral taxon assessed on NCRMP transects, modified by that taxon's history of bleaching within the region. It was calculated as shown in Equation 1.

$$BR_{reg.:sec.} = \sum_{taxon} \left[Abund._{tax.,sec.} * \left(1 - \frac{No.Col.Bleached_{tax.,reg.}}{Total.Col._{tax.,reg.}} \right) \right]$$

Equation 1: Proportion of bleaching resistant corals.

- *Coral diversity:* Generic diversity of corals assessed on NCRMP transects, expressed as the Inverse Simpson's Index.
- *Recruit density:* Hard corals under 5 cm per m^2 assessed on NCRMP transects.
- *Disease density:* Number of diseased colonies per m^2 assessed on NCRMP transects**.**
- *Overfishing:* Percentage of pristine fish biomass exploited, after Williams et al. 2015.
- *Herbivorous fish biomass:* Observed herbivorous fish biomass per unit area, assessed on NCRMP reef fish stationary point counts.
- *Macro-algal cover:* Macroalgal percent cover, assessed on NCRMP photo-quadrat analysis.
- *Temperature variation:* Summer temperature range divided by annual temperature range, from Heron et al. 2016.

An aggregate resilience score was generated by first normalizing all factors to the 5% and 95% ranges of the raw factors (capping outliers at 0 and 1), then summing across all eight factors, and finally re-normalizing the aggregate score by the maximum value of the summed factors.

Social Climate Change Vulnerability Analysis

All social vulnerability data were derived from the American Community Census, analyzed following Kleiber et al. (2018). All measures of social data are compared to domain-wide means across Hawai‘i, American Samoa, and the Mariana Islands (Guam and CNMI). We tied social data to each of the 59 marine ecological sectors by generating a mean of each social index among the CCDs directly adjacent to the ecological sector boundary.

Prioritization Strategies: Rankings & Metrics

Here we aggregate “prioritization sets,” subsets of 59 reef sectors across the total analysis domain, differentially prioritized according to one of six strategies. For each strategy, we rank the sectors according to the ability of each to increase the strategy’s metric with the addition of another single sector, randomizing for ties. We ran 100 distinct randomizations for each level prioritization effort under each strategy (or 5,900 randomizations per strategy, a total of 35,400 randomizations) and calculated each of the six metrics for every prioritization set. For each of the six prioritization strategies, we calculated a performance metric that we applied to the set of sectors under prioritization following an increasing number of sectors (and/or reef area) committed to a particular strategy.

Prioritize *resilience*: Under the *resilience* strategy, we rank sectors according to the resilience score from the climate change vulnerability analysis described above under “Ecological Climate Change Vulnerability Analysis.” The *resilience* prioritization set metric is the mean resilience score across all prioritized sectors (Figure 2).

Prioritize *thermal refugia*: Under the *thermal refugia* strategy, we rank sectors starting with the latest year to the onset of annual recurrence of coral bleaching-relevant thermal stress exposure, following Van Hooidonk et al. (2016). The *thermal refugia* metric is the mean of the year to annual bleaching onset across all prioritized sectors (Figure 3).

Prioritize *biodiversity*: Under the *biodiversity* strategy, we rank sectors by fish/coral taxonomic diversity, starting with the sector with the greatest taxonomic richness, and successively ranking sectors according to the increase in richness, that is, by the highest number of taxa in a sector not yet included in the prioritization set. The *biodiversity* metric is percent of total domain fish/coral taxa present in all prioritized sectors. Fish are all identified to the species level, while corals are identified to either species or genus level, using categories described in Appendix A (Figure 4).

Prioritize *Spatial Representation*: Under the *spatial representation* strategy, we rank sectors on their contribution to increasing the prioritized set’s spatial representation with the least reef area prioritized (i.e., reef area serves as a cost function). Starting with the sector with the least reef area, sectors are added to maximize the metric $SR=P_R*P_I$ with the least addition of reef area, where P_R is the proportion of regions represented in the prioritized set (i.e., 1 to 5 over a total of 5 regions), and P_I is the proportion of islands represented in the prioritized set (i.e., 1 to 37 over a total of 37 islands). The *spatial representation* metric is SR value calculated for the prioritized set (Figure 5).

Prioritize *resource fish biomass*: Under the *resource fish biomass* strategy, we rank sectors starting with the greatest biomass of commercially targeted “resource” fish and add to the prioritization set in the order of the greatest biomass. The *resource fish biomass* metric is the percentage of total domain resource fish biomass captured within the prioritized set. The taxa included as resource fish are listed in Appendix B. We extrapolated resource fish biomass per unit area measured by NCRMP to total sector biomass using reef area (Figure 6).

Prioritize *social vulnerability*: Under the *social vulnerability* strategy, we rank sectors starting with the high aggregate social vulnerability, following Kleiber et al. (2018). The *social vulnerability* metric is the mean of the aggregate vulnerability scores (ranging from 0−5) for all prioritized sectors, with higher values indicating higher vulnerability (Figure 7).

Comparing Trade-offs/Efficiency Frontiers

To compare the relative trade-offs among “pure” strategies, we first plot all strategies’ performance against each metric, with increasing commitment to prioritization represented by reef area under prioritization (Figures 9−14).

We then evaluate efficiency frontiers, comparing the relative trade-offs between the prioritization set’s resilience metric and each of the other five metrics. The shape of the efficiency frontier describes the degree to which a given prioritization set constitutes a “win-win” between two distinct metrics, and how this trade-off changes with varying degrees of commitment to prioritization (White et al. 2012). We compare efficiency frontiers of each metric against the resilience metric for the *resilience* strategy and each other strategy in each trade-off space (Figures 15−19).

Results

Setting the Scope of this Analysis

In this analysis, we explore spatial prioritization across a broad spatial scale covering a range of 6,500 km in the Central Pacific, spanning 40 degrees of latitude and 75 degrees of longitude. At this broad spatial coverage, we use data summarized to 59 reef survey sectors that either cover all of a small island or divide an island into sectors with a median reef area of about 1,513 hectares, or a square 4 km on each side if pushed into a single coherent block.

In our analysis, we do not specify what form of management action would or should occur in the prioritized set; in reality, several approaches would likely be necessary. Nor do we advocate any one of the “pure” strategies proposed here. Our goal is merely to explore how resilience metrics can interact with other prioritization objectives to help guide the crafting of climate-informed management responses.

Ecological and Social Vulnerability Assessment

The nested maps shown in Figure 1 highlight each U.S.−Affiliated Pacific Island, showing the aggregate resilience index along the coast and the social vulnerability index within CCDs on land. We see that many remote areas show relatively high resilience, including many of the islands across the Pacific Remote Island Marine National Monument, but remoteness itself is not a guarantee of resilience, as islands in Papahānaumokuākea Marine National Monument range from medium-high to low resilience. Many areas around population centers in Oʻahu, Maui, S. Tutuila, and Guam show low resilience. Social vulnerability indices show low vulnerability in Hawaiʻi and Guam, higher vulnerability in Tinian, Saipan, and American Samoa, and exclude many of the remote uninhabited islands.

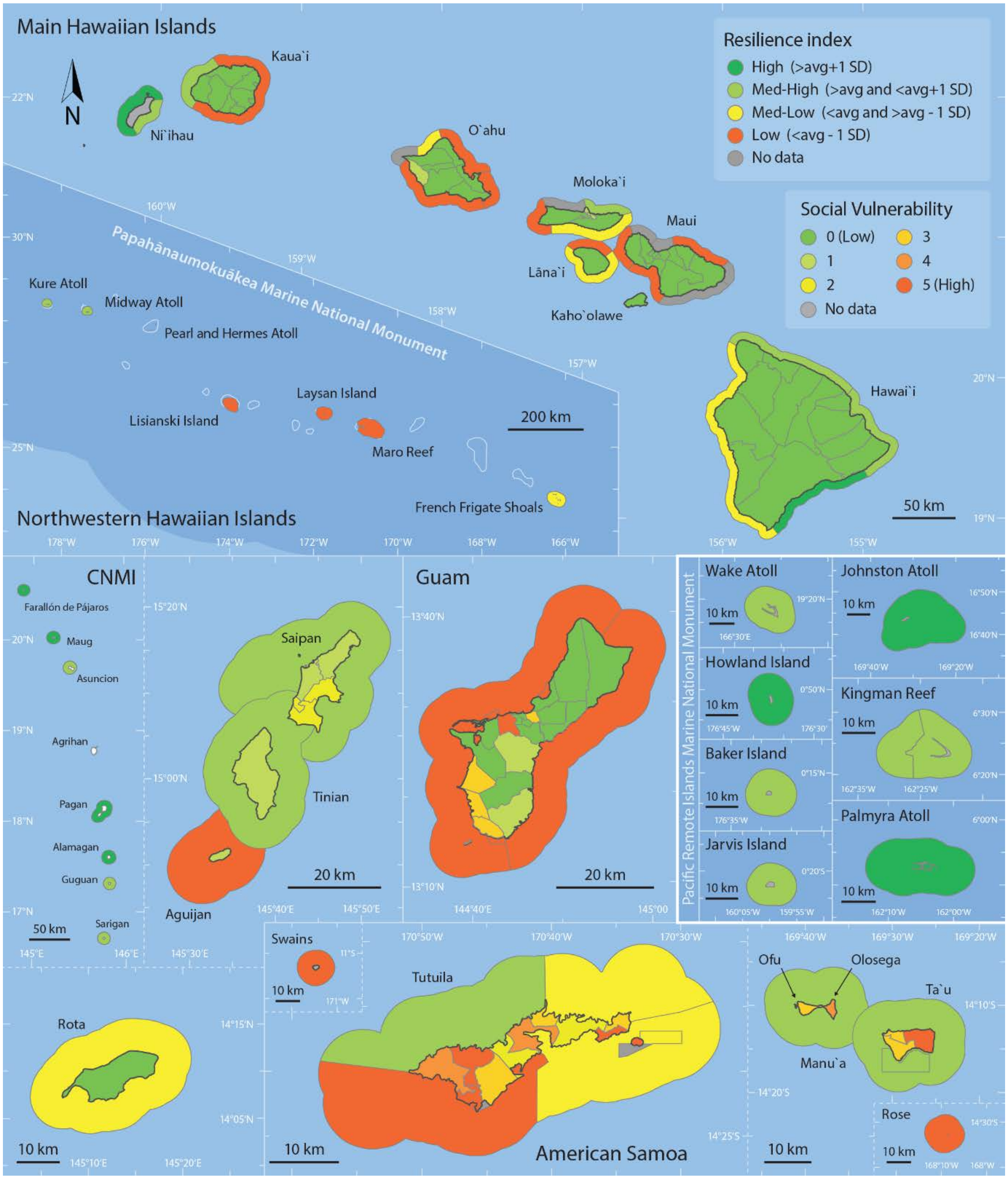


Figure 1: Climate change vulnerability assessment results

Prioritization Strategies in Isolation

The maps in Figures 2−7 show the mean rankings of each reef sector (from 100 randomized runs) for each of the six prioritization strategies.

Rank order of selection under the *prioritize resilience* strategy (Figure 2) directly follows the ecological results of the climate change vulnerability estimate shown in Figure 1, with highest priority going mostly to remote areas in the PRIMNM, in the northern islands of the CNMI, and more lightly populated regions in American Samoa and Hawaiʻi. That said, the remote areas of Papāhanaumokuākea MNM (NWHI) remain low resilience and show up as low priority according to this strategy.

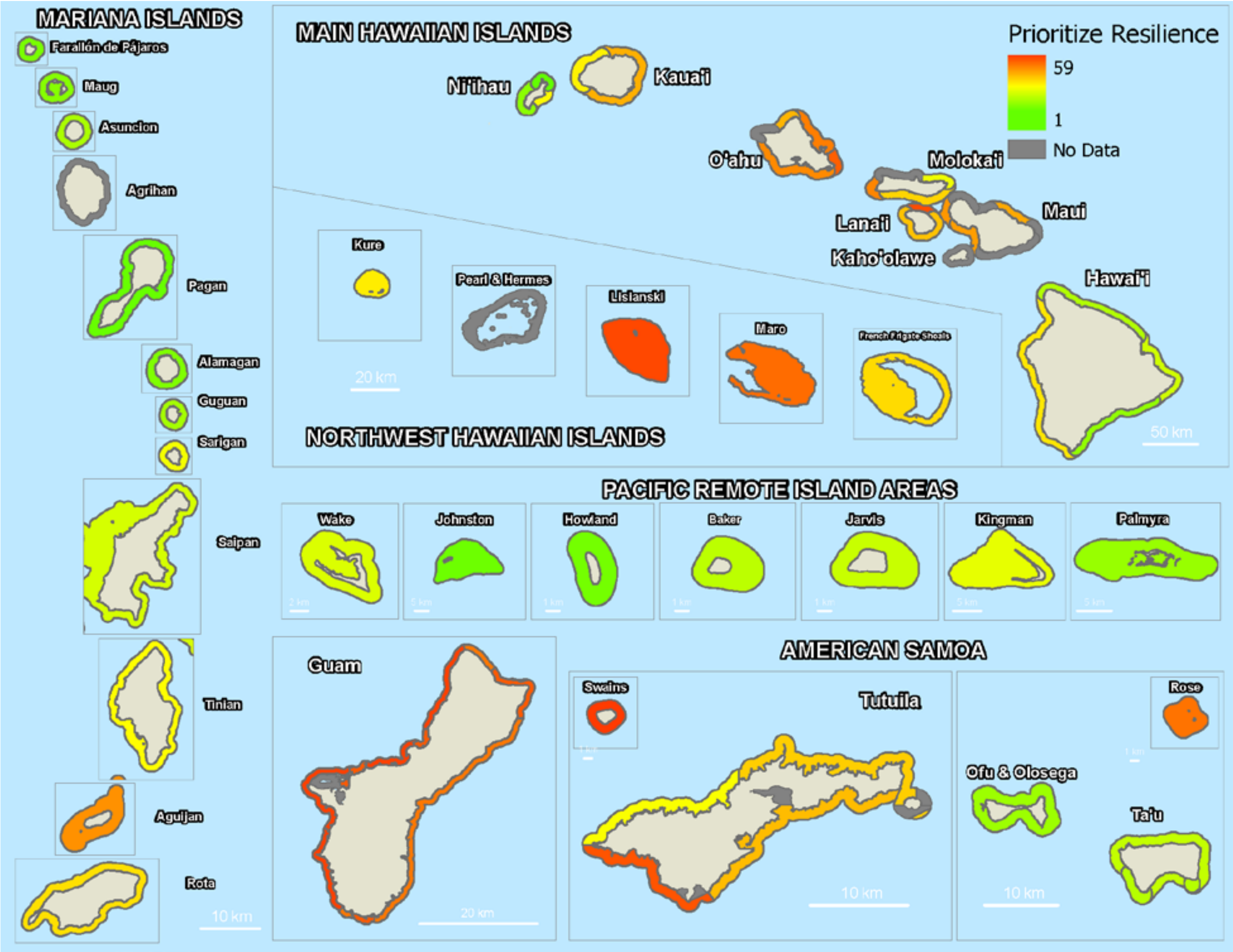


Figure 2: Rank order of sector prioritization under the strategy: prioritize resilience.

Following the *prioritize thermal refugia* strategy (Figure 3), we see that the first selected areas are in Papāhanaumokuākea MNM (NWHI), and the last selected are Guam and the southern islands in CNMI. Both the main Hawaiian Islands and American Samoa are moderate in this prioritization.

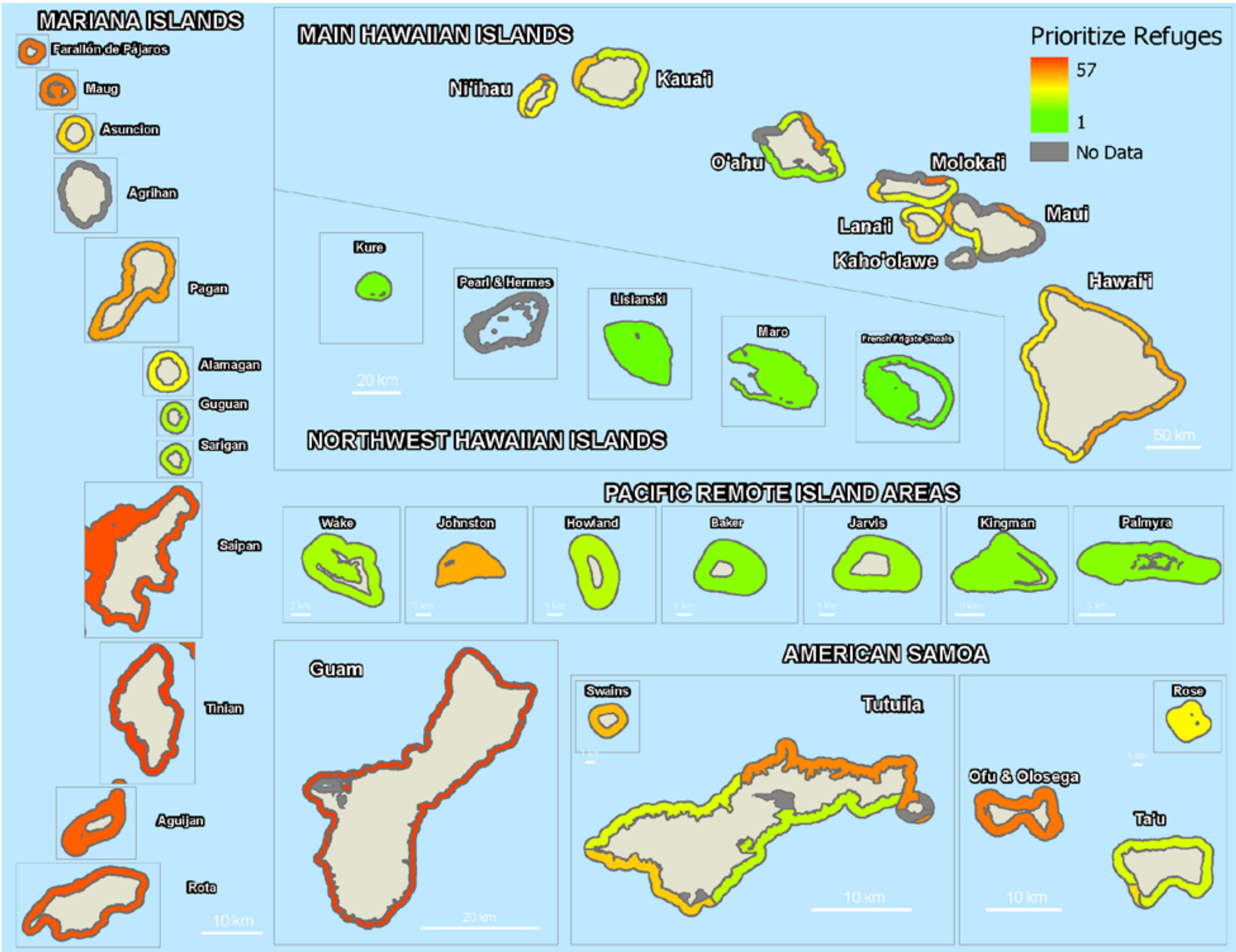


Figure 3: Rank order of sector prioritization under the strategy: prioritize thermal refugia.

Following the *prioritize biodiversity* strategy (Figure 4), we see that American Samoa, Guam, the PRIMNM, and the southern islands in the CNMI are selected, along with a representative few sectors in Hawai'i. Once the initial pass to 'collect' taxa in this representative framework has occurred, the low-diversity, high-endemism reefs in Hawai'i and NWHI islands are last to be included.

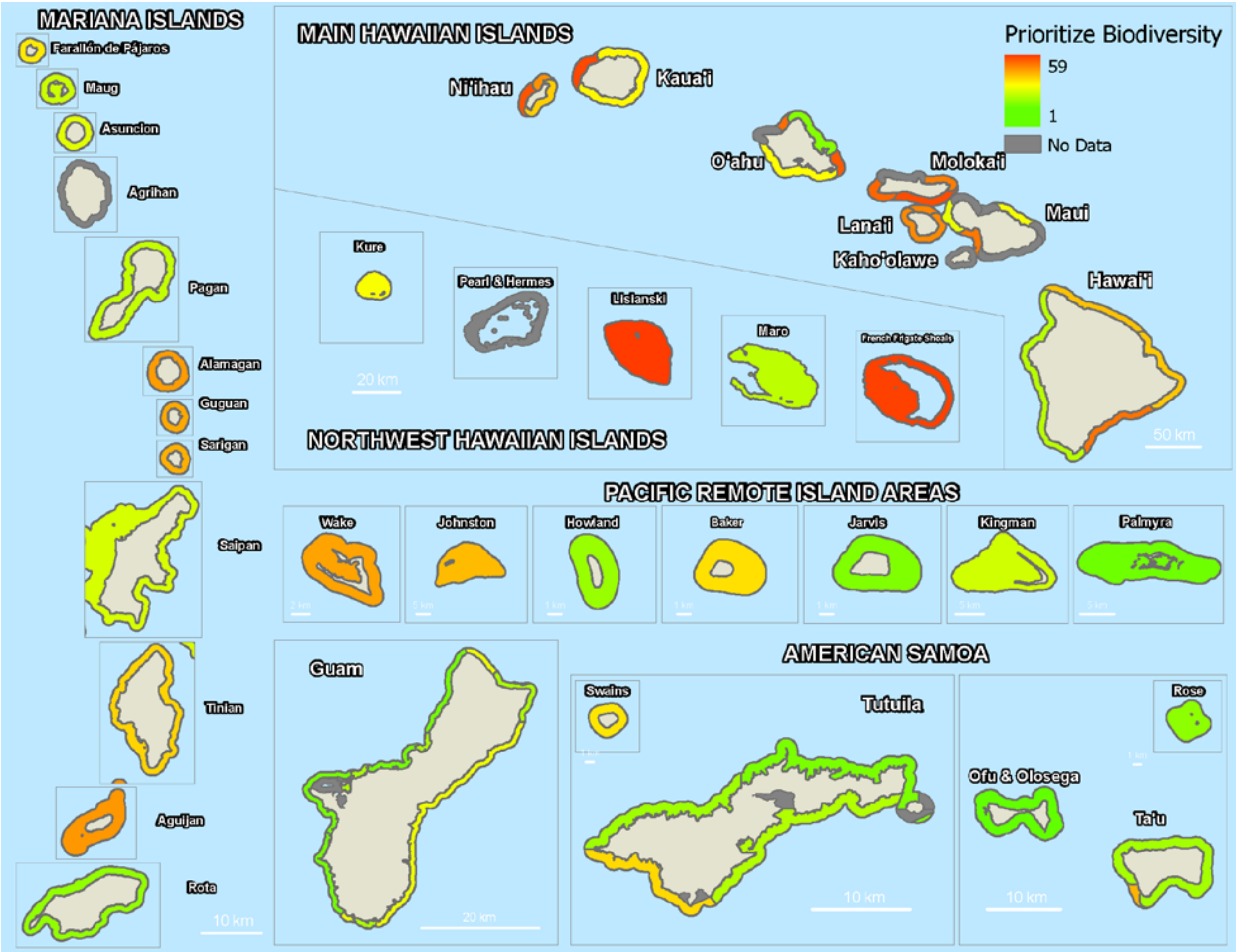


Figure 4: Rank order of sector prioritization under the strategy: prioritize biodiversity.

Following the *prioritize spatial representation* strategy (Figure 5), there is a clear pattern of representation, leading with the small reef area sectors in each island/region, with the islands/regions with multiple sector per island following last. In reality, the order of addition for this strategy is less important than the performance of any prioritized set according to this metric.

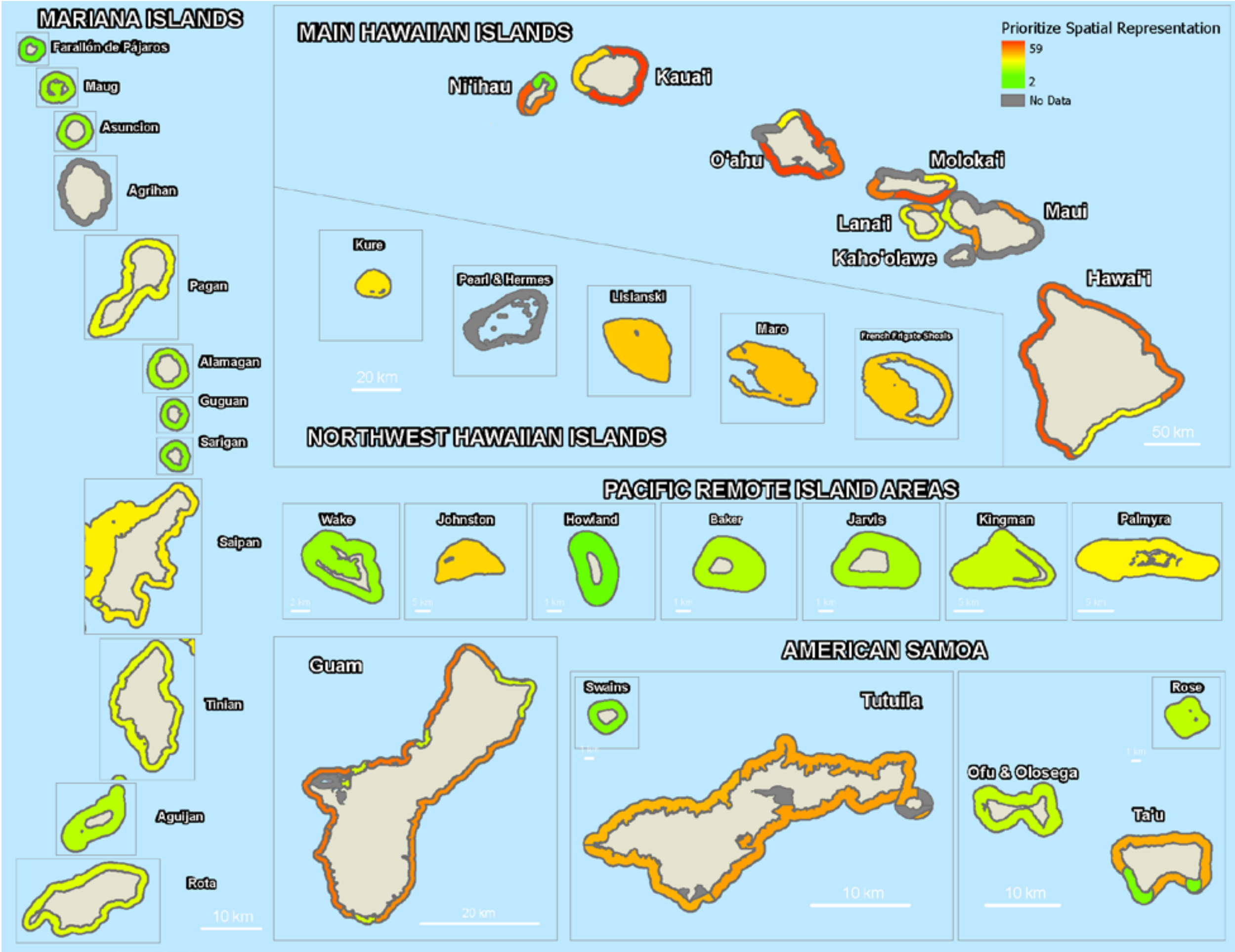


Figure 5: Rank order of sector prioritization under the strategy: prioritize spatial representation.

The *prioritize resource fish* strategy (Figure 6) demonstrates the dominance of large reef area sectors with high resource fish biomass per unit area. In particular, the remote areas in NWHI, Palmyra, and particularly Johnston Atoll dominate the early rankings, along with the large reef sectors along Hawai‘i Island.

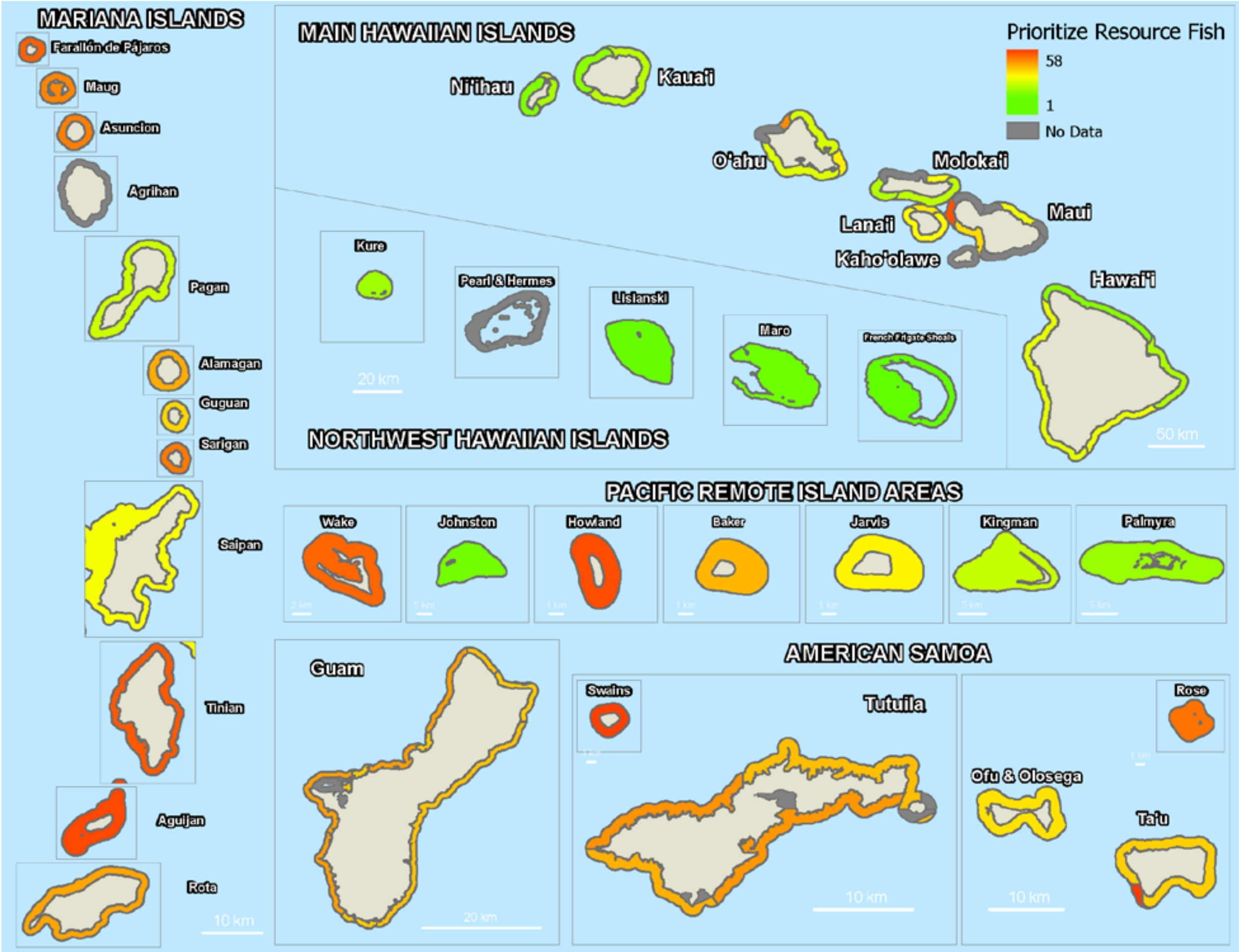


Figure 6: Rank order of sector prioritization under the strategy: prioritize resource fish.

Finally, the *prioritize social vulnerability* strategy (Figure 7), first shows us that many reefs across the domain are unpopulated by humans and therefore there are no social data available. However, using a domain-wide standard that compares metrics equally across Hawai‘i, Guam, CNMI, and American Samoa, we see that social vulnerability is high in American Samoa, lower in Guam and CNMI, and then low across most of Hawai‘i. Sectors are prioritized in that order.

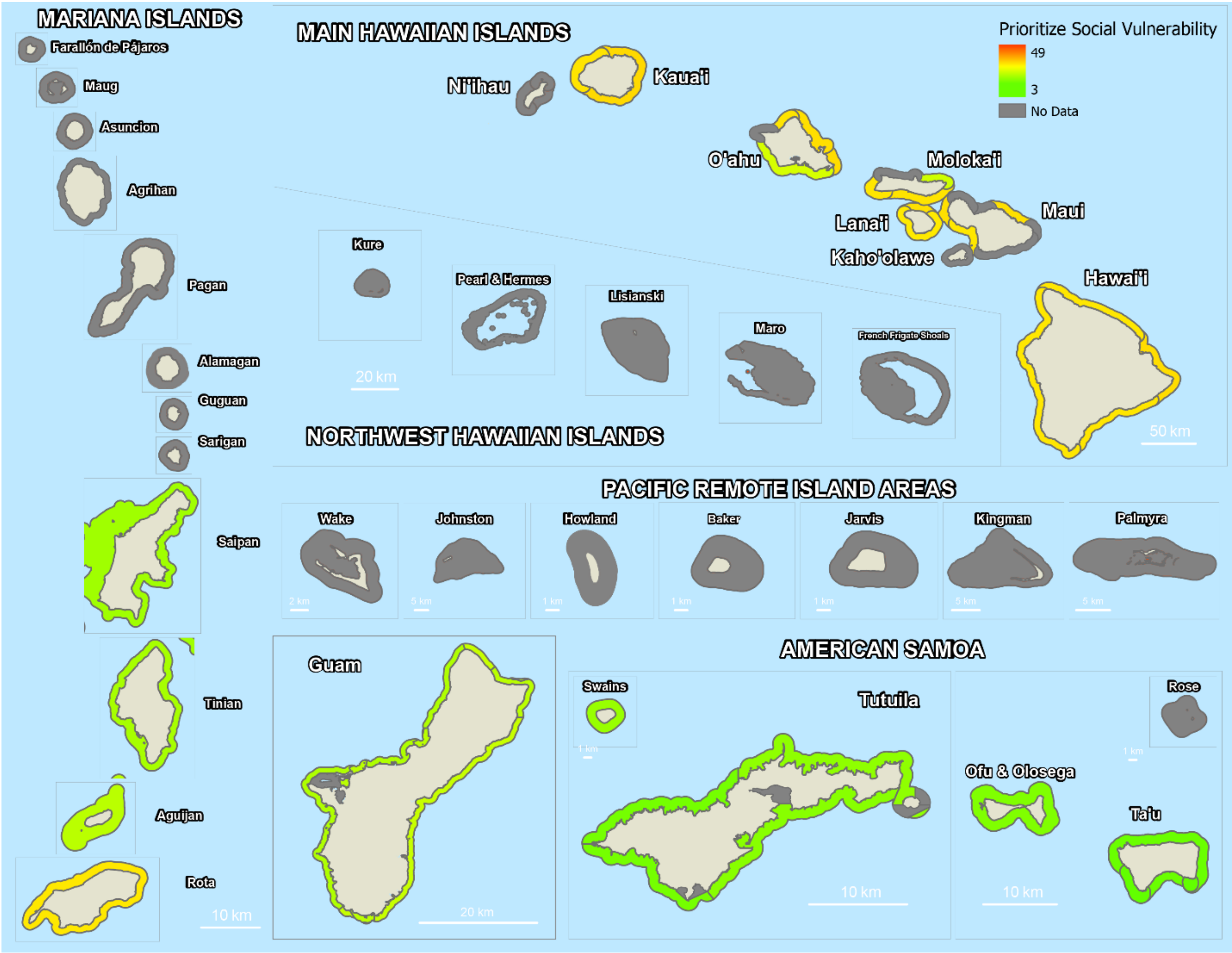


Figure 7: Rank order of sector prioritization under the strategy: prioritize social vulnerability.

Prioritization Strategy Performance by Strategy Metric

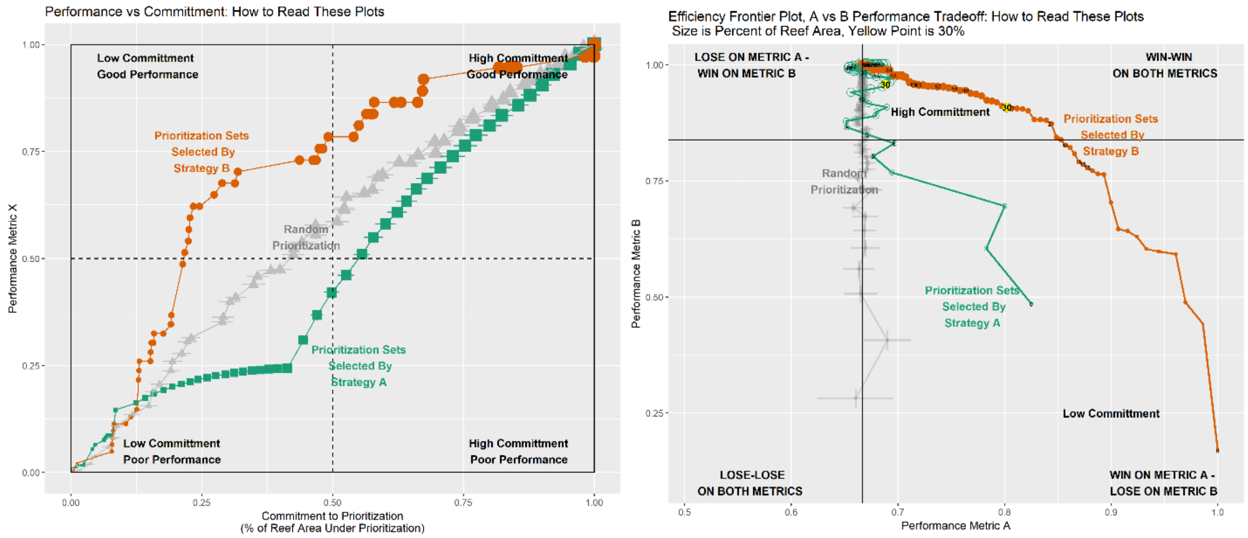


Figure 8: How to read: (A) the performance vs. commitment plots and (B) the efficiency frontier plots.

In the following six figures, we present the performance of each strategy's prioritized sets running along a gradient of low to high commitment (i.e., reef area prioritized) for each strategy's performance metric, following the standard laid out in Figure 8A. In each plot, the grey points/line represent the mean and 95% confidence limits of a random selection of sectors.

Comparing all six strategies' performance on the *resilience* metric (Figure 9) shows that only *prioritize resilience* performs well across all prioritization sets, especially in low commitment scenarios. Interestingly, the strategies prioritizing social vulnerability, resource fish, and thermal refugia all perform substantially worse than a random collection of sectors.

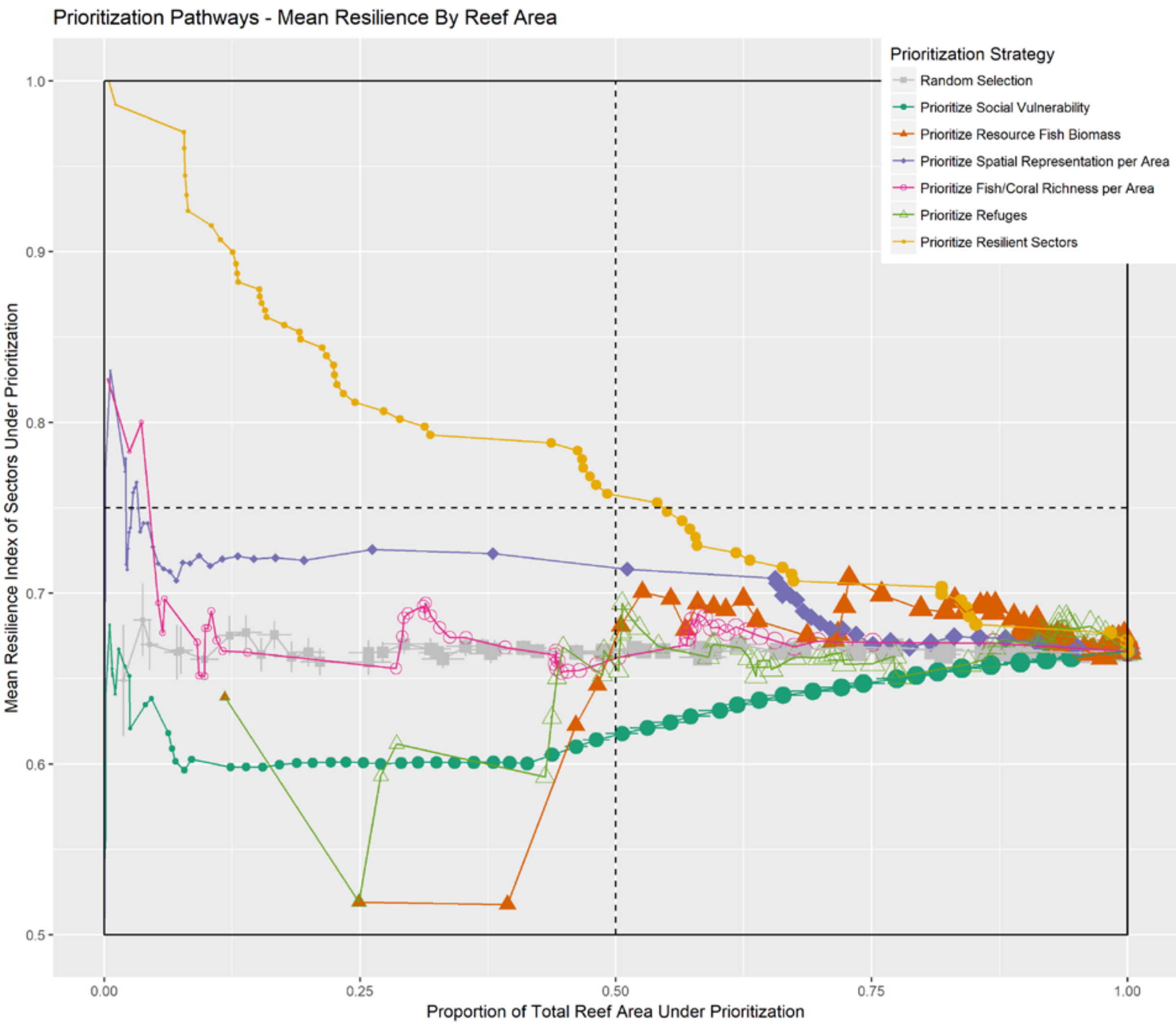


Figure 9. Performance of the prioritized set on the resilience metric by prioritization strategy with an increasing proportion of total reef area included in the prioritized set.

Comparing all six strategies in their performance on the *thermal refugia* metric (Figure 10) shows us that thermal refugia and resource fish biomass strategies track together well, but resilience as a strategy performs quite poorly. Social vulnerability also performs substantially worse than random sets.

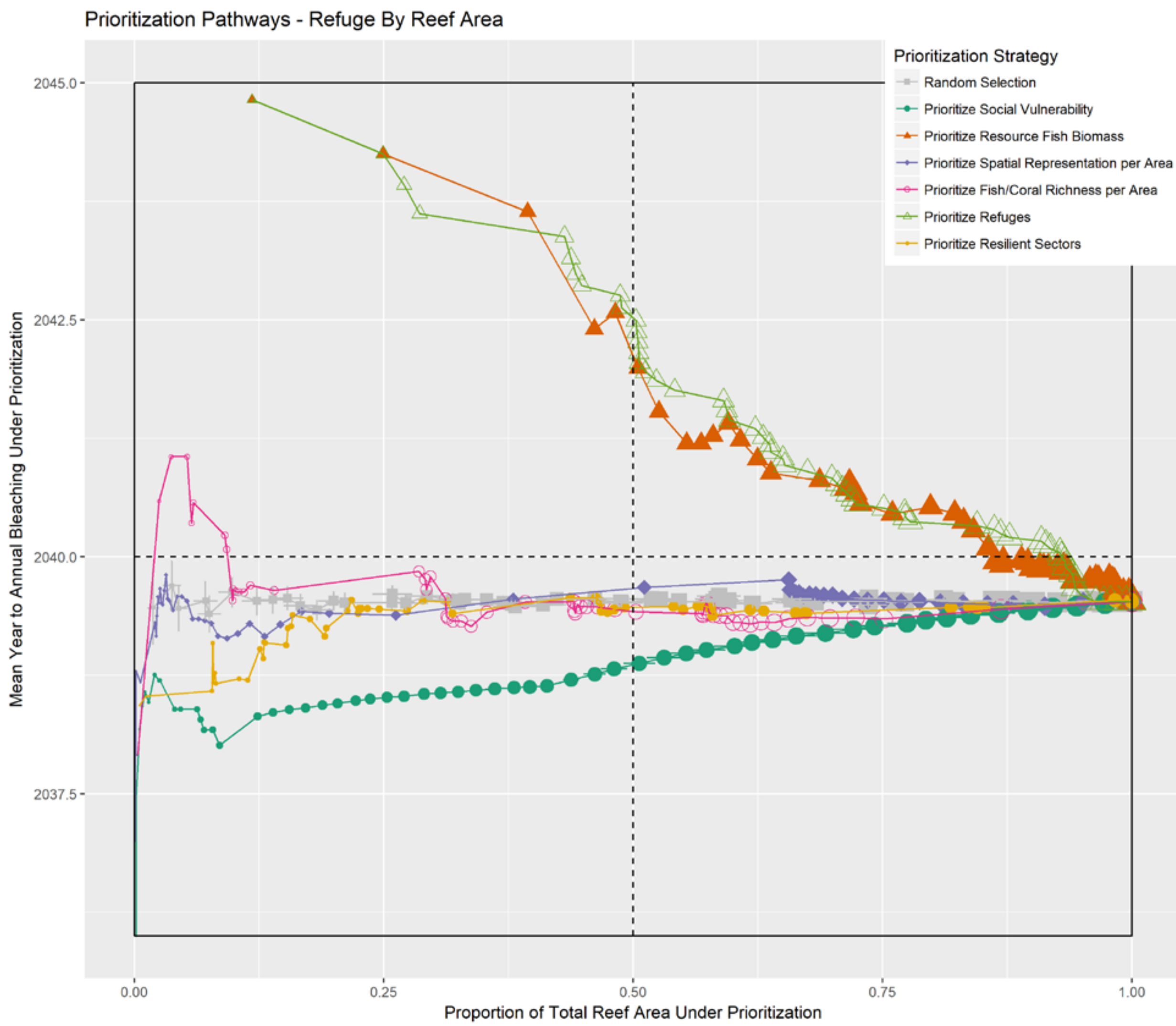


Figure 10: Performance on the thermal refugia metric by prioritization strategy with an increasing proportion of total reef area included in the prioritized set.

Comparing performances on the *spatial representation* metric (Figure 11) shows that, while only a strict adherence to spatial representation maximizes this metric with reef area prioritized, both resilience and biodiversity perform substantially better than random, while social vulnerability, thermal refugia, and resource fish biomass strategies perform substantially worse.

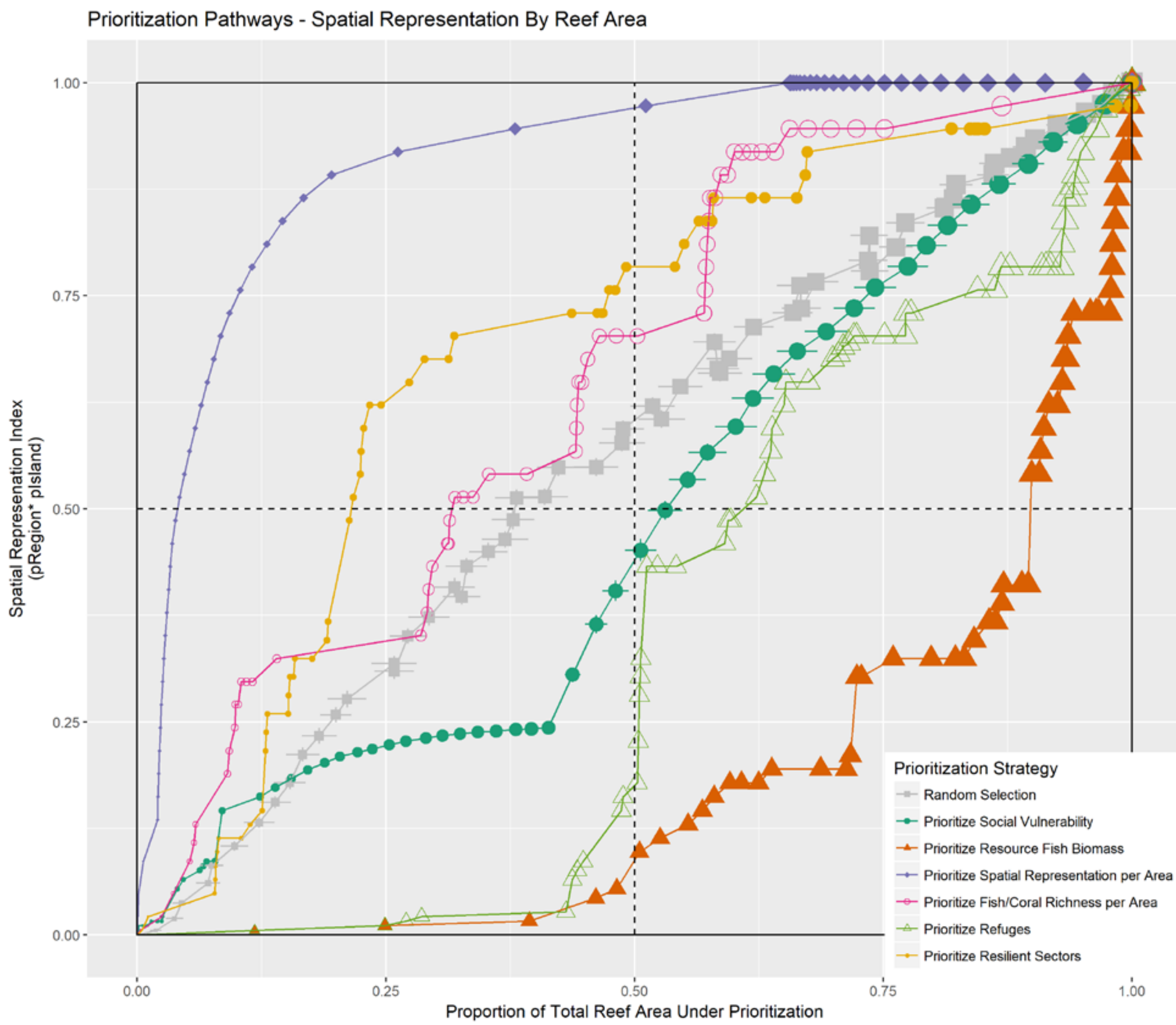


Figure 11: Performance on the spatial representation metric by prioritization strategy with an increasing proportion of total reef area included in the prioritized set.

Regarding the *biodiversity* metric (Figure 12), four strategies perform better than the random selections—biodiversity, spatial representation, social vulnerability, and resilience—in low commitment scenarios (i.e., less than ~30% reef area prioritized). Again, thermal refugia and resource fish biomass strategies perform substantially worse than random on this biodiversity metric.

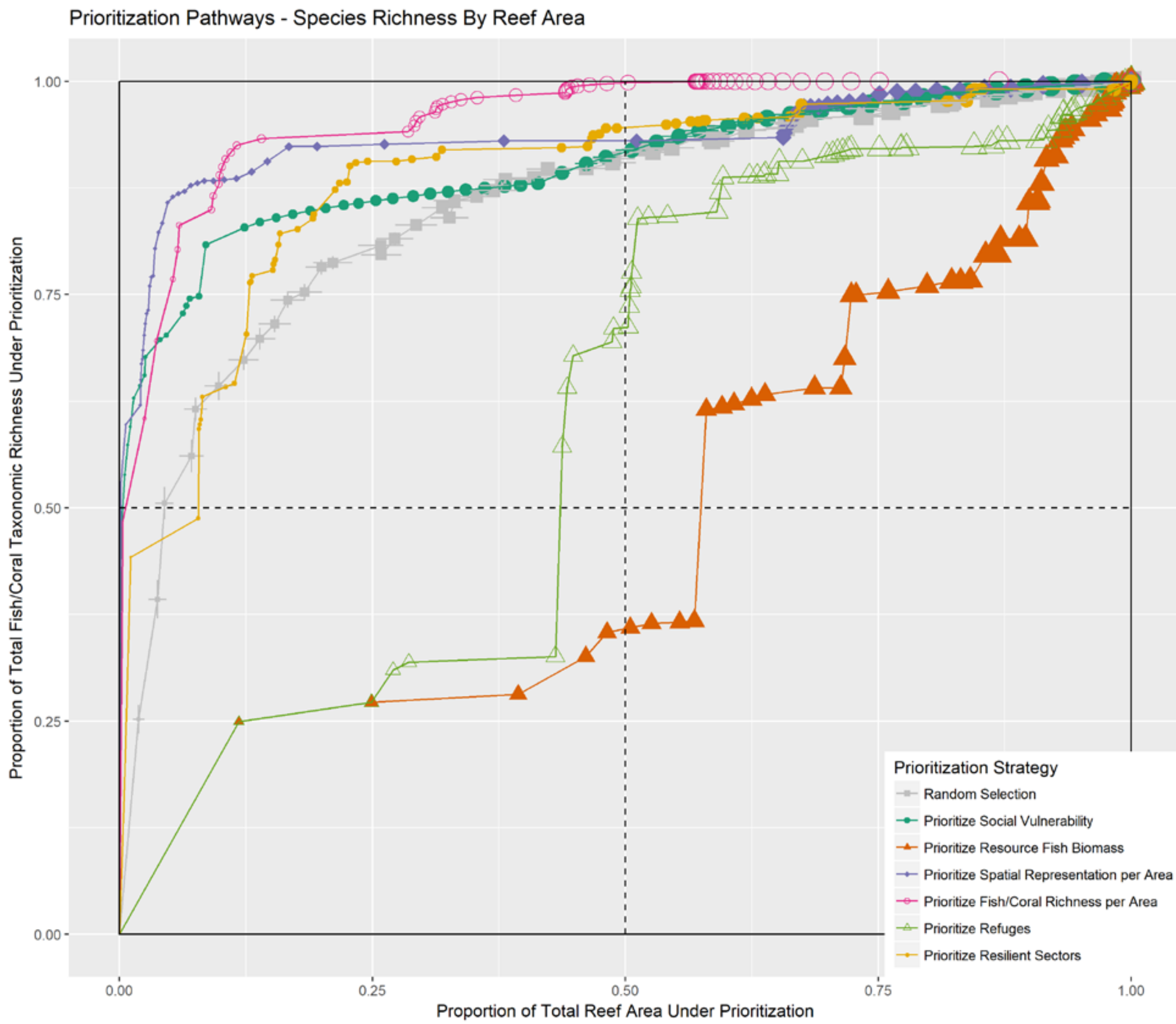


Figure 12: Performance on the biodiversity metric by prioritization strategy with an increasing proportion of total reef area included in the prioritized set.

Using the *resource fish biomass* metric (Figure 13), the thermal refugia strategy follows a similar course as with the resource fish biomass strategy, but both spatial representation and resilience strategies perform variably relative to the random set. However, with substantial commitment (i.e., greater than 40% of area), both spatial representation and resilience strategies can out-perform the random sets. Social vulnerability and biodiversity perform poorly on this metric.

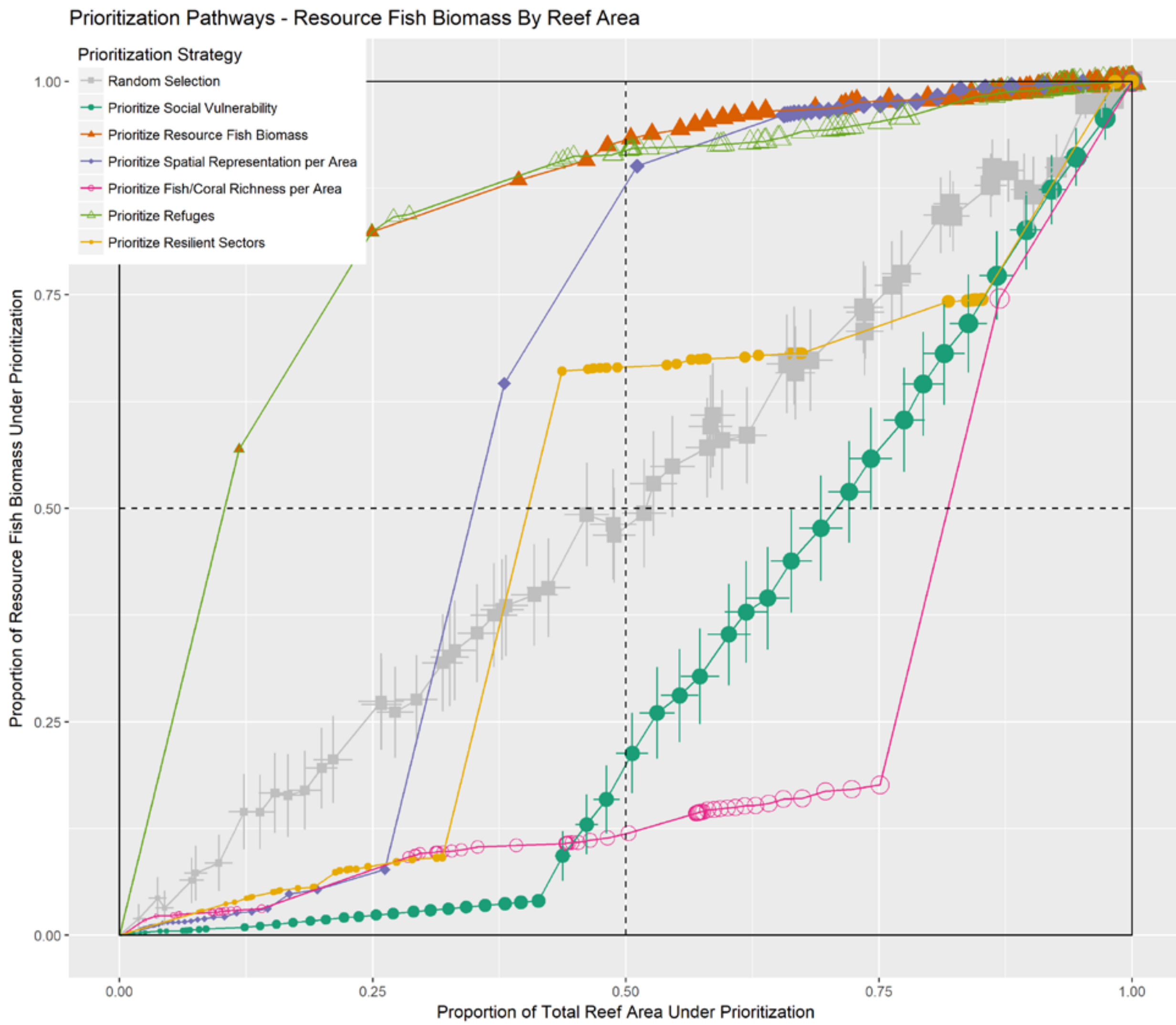


Figure 13: Performance on the resource fish metric by prioritization strategy with an increasing proportion of total reef area included in the prioritized set.

Finally, with *social vulnerability* (Figure 13, Figure 14), we see that social vulnerability, spatial representation, and biodiversity hang tightly together at low commitment but once resilience includes the high resilience remote areas, it quickly adds areas of high social vulnerability and outperforms random from approximately 20% to 30% of reef area committed to prioritization. Resource fish strategy appears to act in direct opposition to social vulnerability.

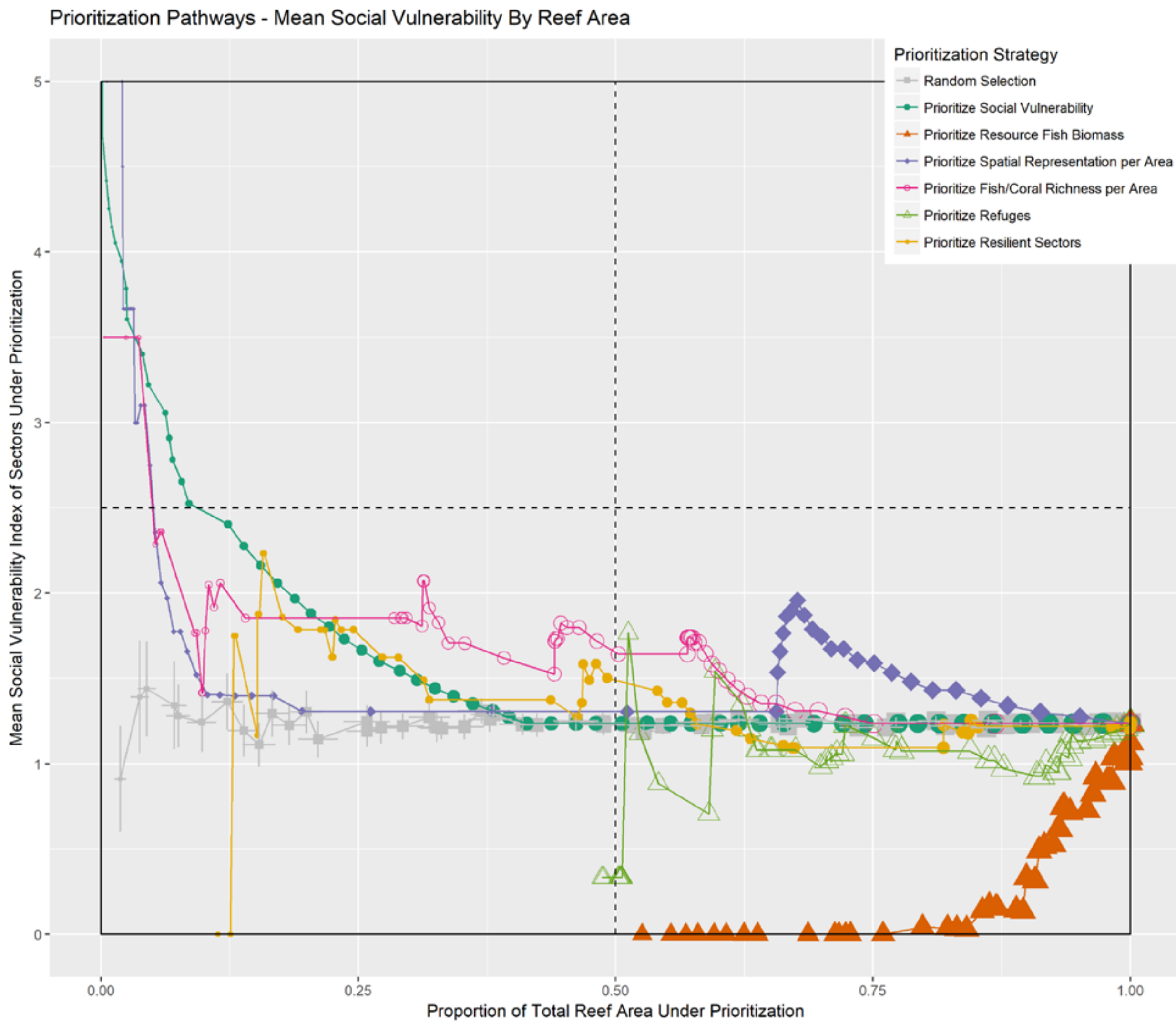


Figure 14: Performance on the social vulnerability metric by prioritization strategy with an increasing proportion of total reef area included in the prioritized set.

Efficiency Frontier Analysis, Comparing Resilience to Five Other Strategies

Now we directly pit two strategies against each other on plots following the standard laid out in Figure 8B. Each point is a prioritized set, each line represents a commitment pathway for a particular strategy, and the position of a point in X-Y space conveys simultaneous performance on two metrics. Points falling in the upper right quadrant of these plots convey a "win-win" between two metrics, a situation where the prioritized set performs well on both metrics. Points in either the upper left or lower right convey a trade-off ("win-lose")—a set that does well in one axis, but poorly on the other. We would expect few points to fall in the lower left ("lose-lose") as each strategy displayed here was optimized for one of the performance metrics. We show commitment to a strategy (i.e., % reef area) as the size of the point and as a number superimposed on some of the points. As a reference, we highlight the point nearest to 30% reef area, a common target for protected area networks.

Beginning with *resilience* vs. *thermal refugia* (Figure 15), there is no point on the commitment pathways for either strategy do we see substantively better than random performance on both—i.e., no points appear to be "win-win." This suggests that *resilience* and *thermal refugia* directly trade-off with each other and that neither strategy will provide a prioritized set that supports the other metric.

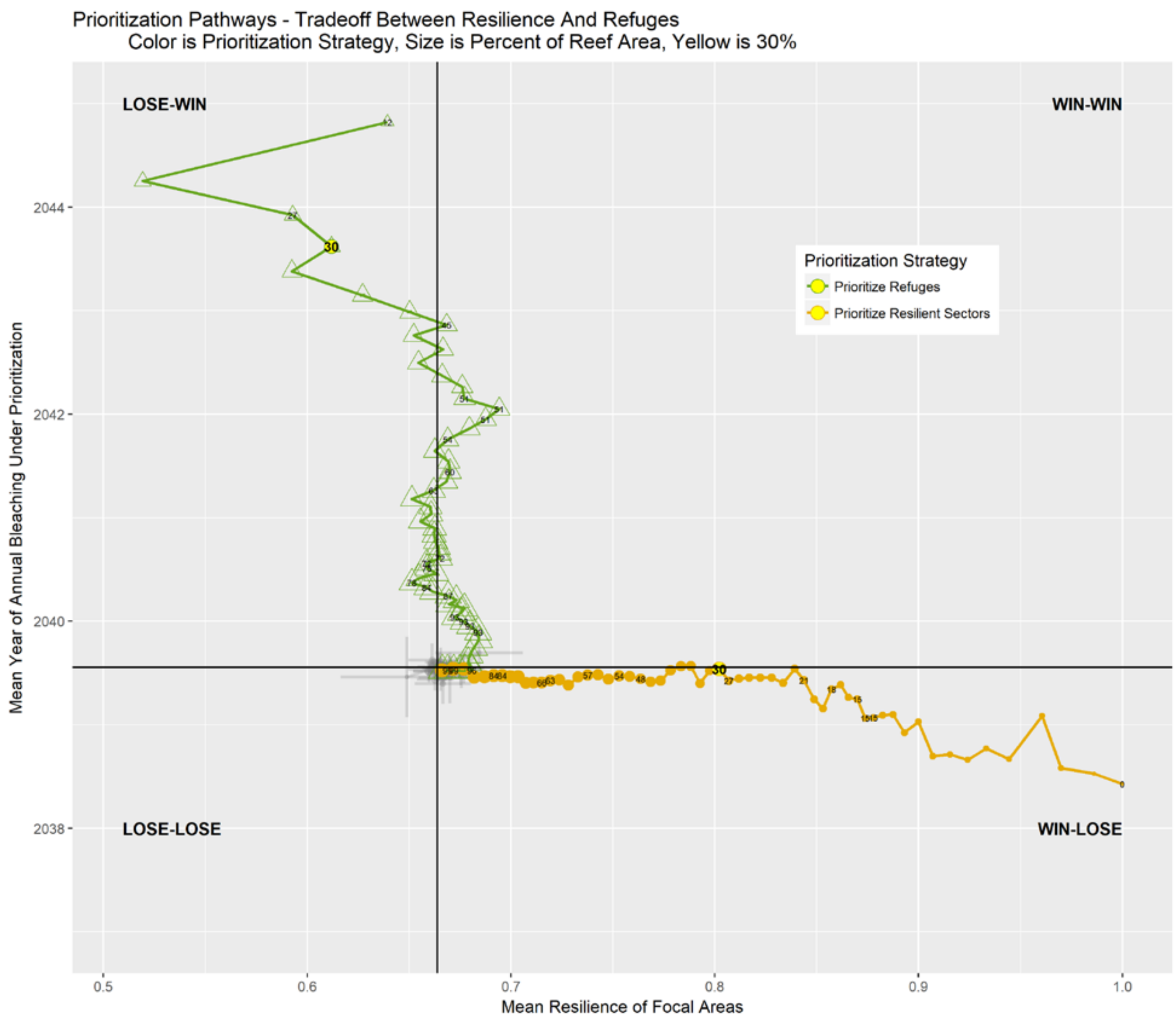


Figure 15: Efficiency frontier—trade-off between resilience and thermal refugia strategies.

Resilience vs. *spatial representation* (Figure 16) produces a different pattern. Both strategies produce sets that perform well on both metrics ("win-win"), even at moderate levels of prioritization commitment (20% to 30% of reef area). Of the two, however, *resilience* better balances the requirements of both metrics, as shown by the *resilience* line's position closer to the upper right corner of the plot.

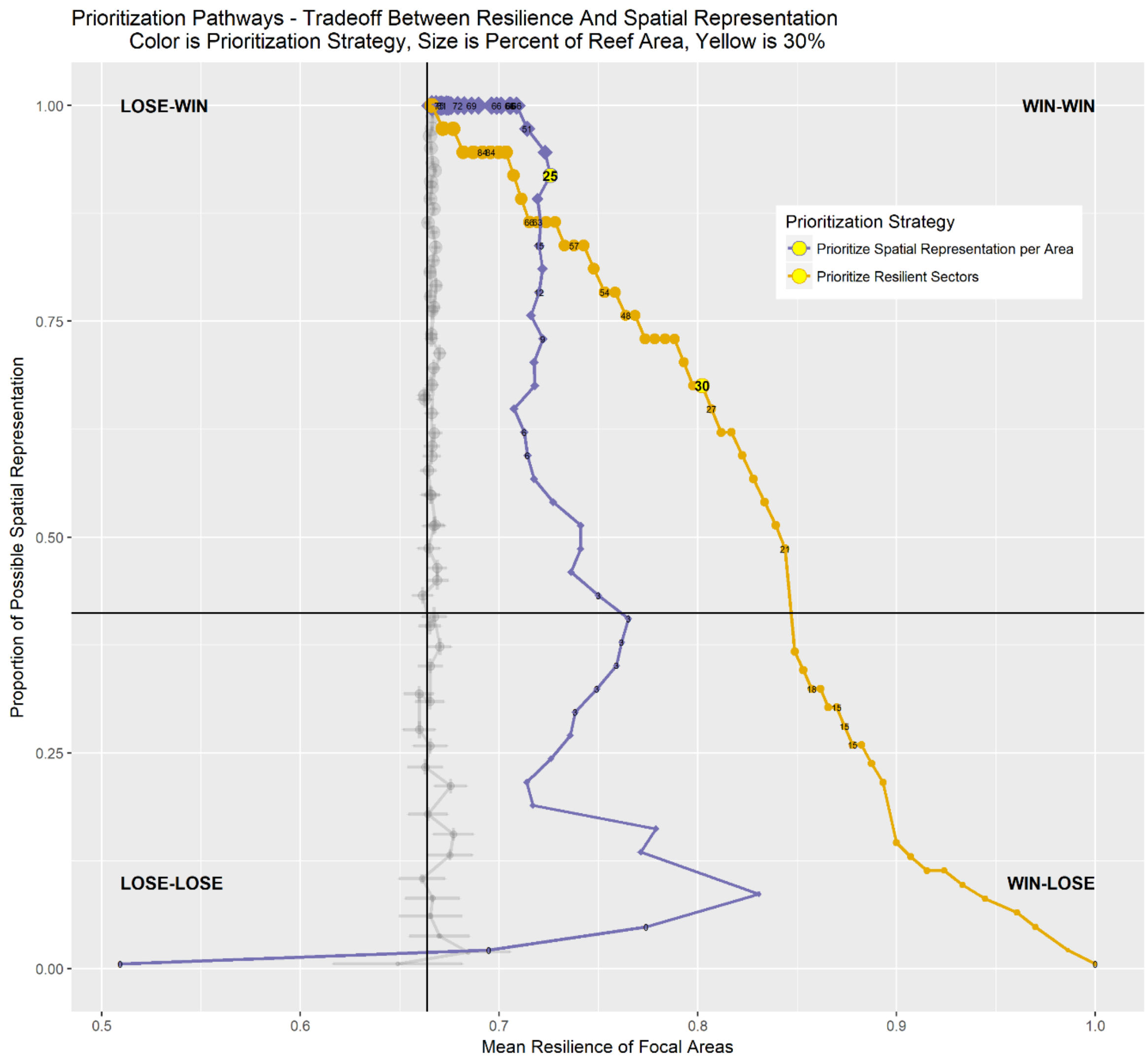


Figure 16: Efficiency frontier—trade-off between resilience and spatial representation strategies.

Resilience vs. *biodiversity* (Figure 17) yields different pattern yet again. Here, *resilience* performs well on both metrics after a commitment of about 20% of reef area and closely approaches the “win-win” corner. The *biodiversity* strategy, however, performs well on its own metric but never selects a set that performs well on the resilience metric.

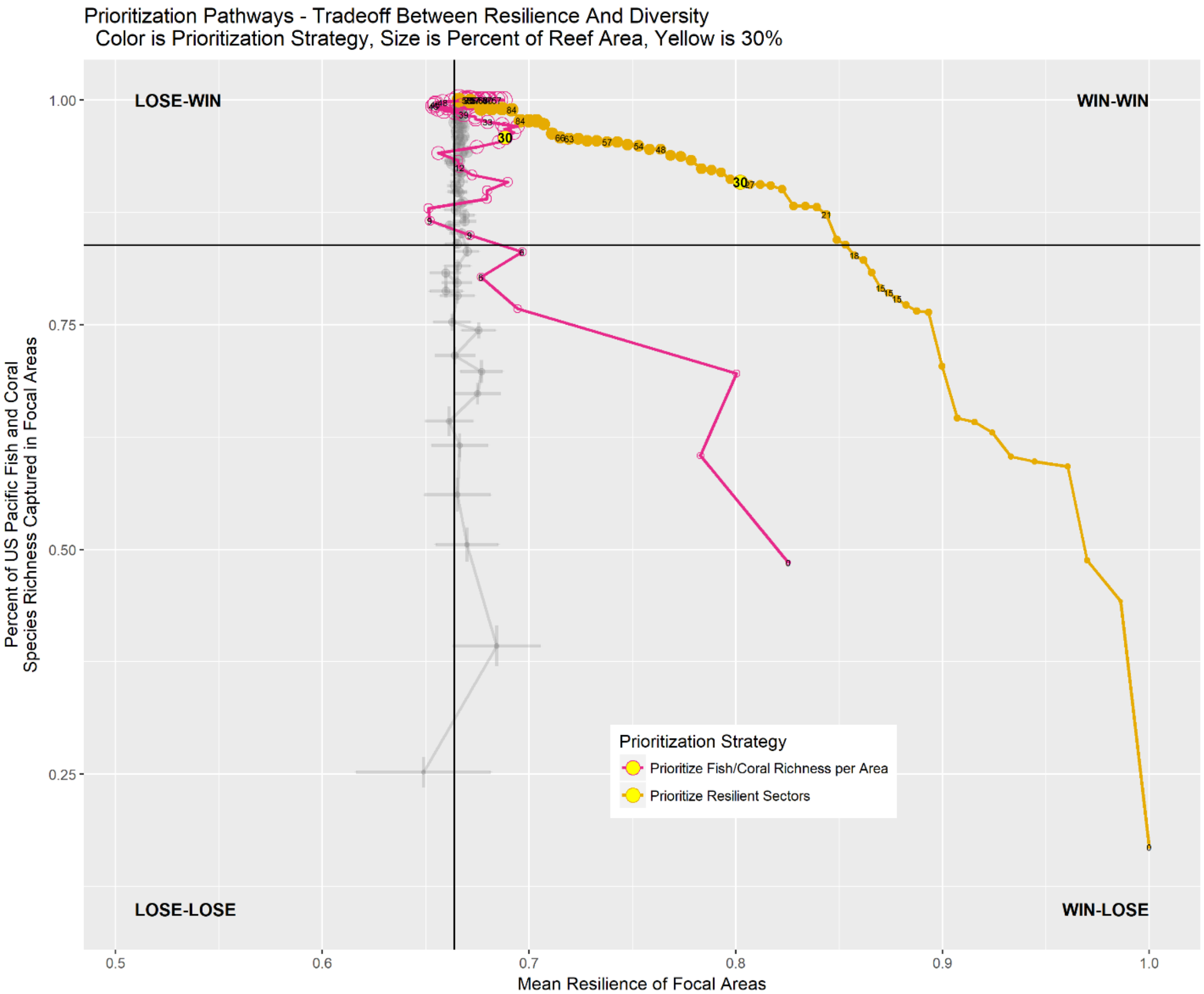


Figure 17: Efficiency frontier—trade-off between resilience and biodiversity strategies.

In the case of *resilience* vs. *resource fish biomass* (Figure 18), neither strategy performs well on their complementary metric at low levels of prioritization commitment. However, with large enough commitment (around 40% of reef area), *resilience* produces prioritization sets that generate “win-win” outcomes.

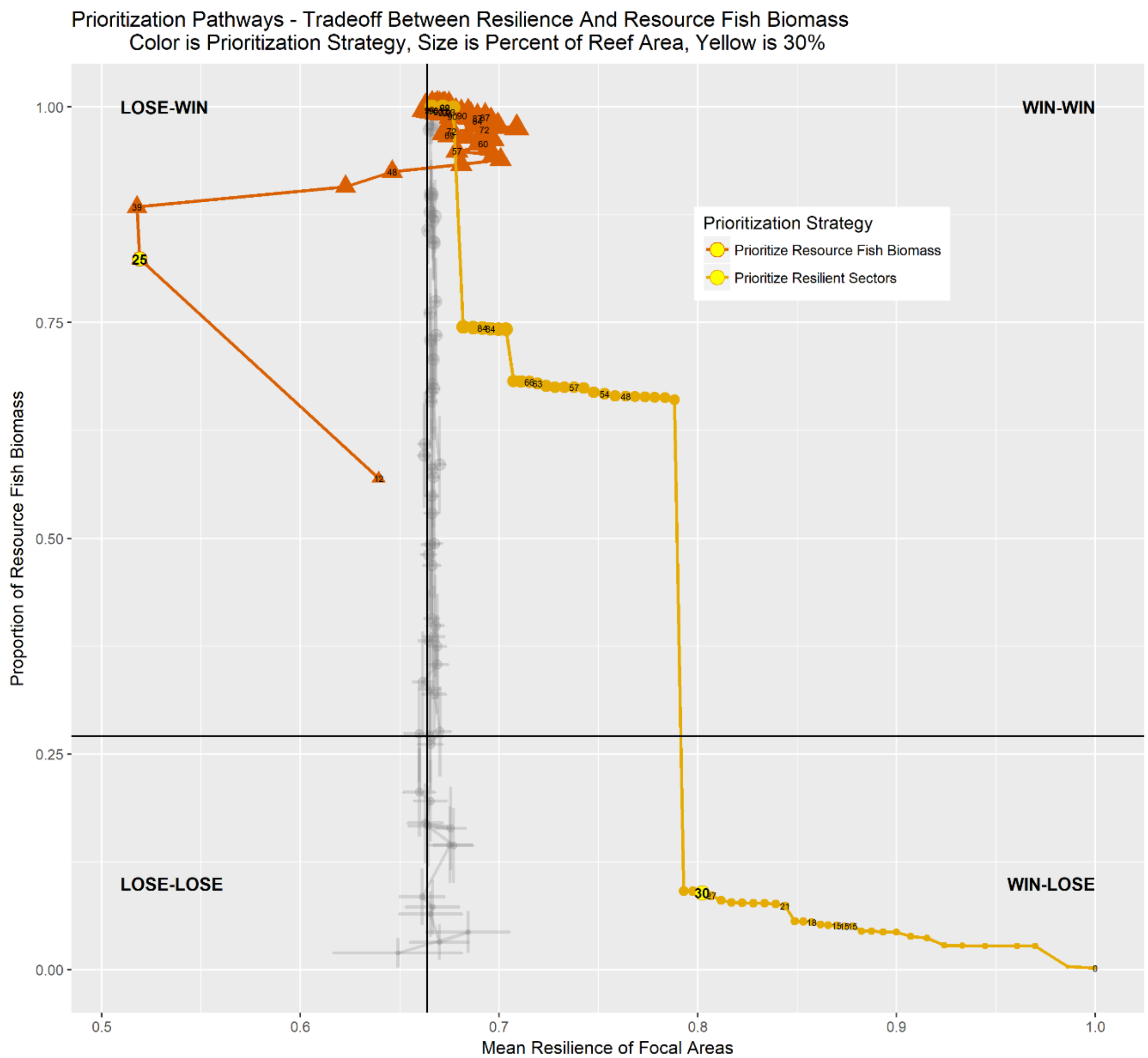


Figure 18: Efficiency frontier—trade-off between resilience and resource fish strategies.

Finally, *resilience* vs. *social vulnerability* (Figure 19) shows that resilience once again performs well on both metrics at moderate levels of commitment, while prioritizing social vulnerability usually performs substantially poorer than random on resilience metrics.

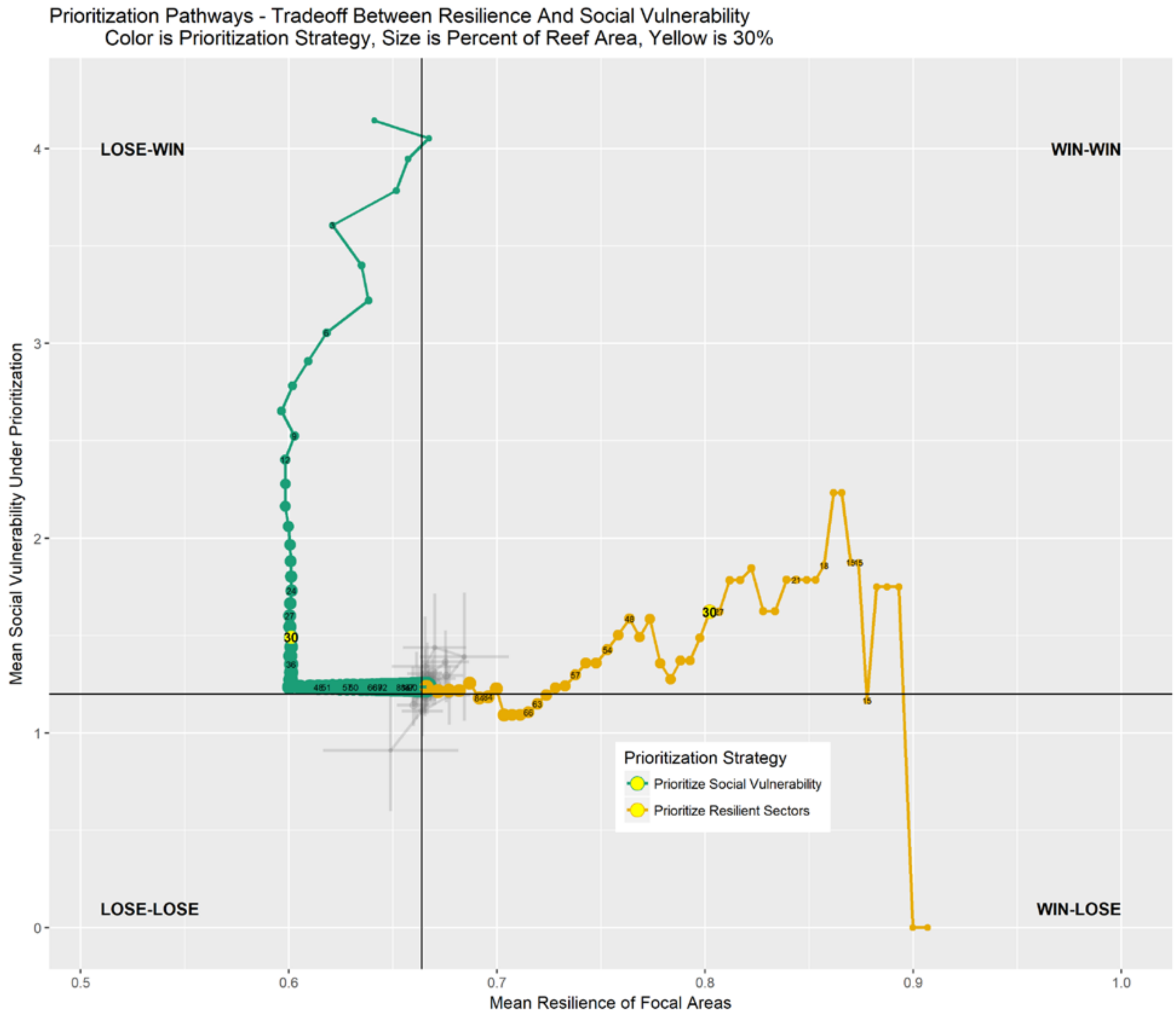


Figure 19: Efficiency frontier—trade-off between resilience and social vulnerability strategies.

We summarize the efficiency frontier results in Table 1, which shows that the *resilience* strategy delivers win-win outcomes on all metrics except *thermal refugia.* Also, delivering a win-win on *resource fish biomass* requires substantial commitment to the prioritization strategy, with around 40% of reef area prioritized.

From the opposite perspective, both *spatial representation* and *biodiversity* strategies can provide win-win outcomes on resilience, while *thermal refugia*, *resource fish*, and *social vulnerability* fail to produce prioritization sets that perform well on the resilience metric.

Table 1: Trade-offs with resilience strategy & metric using other prioritization strategies.

Prioritization Strategy	Metric Evaluating Trade-off	Trade-off Metric at 30% Reef Area Prioritized	Tangency Commitment With Pure Strategy
Resilience	Thermal Refugia	Win-Borderline	30%
Resilience	Spatial Representation	Win-Win	40%
Resilience	Biodiversity	Win-Win	21%
Resilience	Resource Fish	Win-Win @ 40%	40%
Resilience	Social Vulnerability	Win-Win	16%
Thermal Refugia	Resilience	Win-Lose	51%
Spatial Representation	Resilience	Win-Win	25%
Biodiversity	Resilience	Win-Borderline	32%
Resource Fish	Resilience	Win-Lose	85%
Social Vulnerability	Resilience	Win-Lose	2%

Discussion

Resilience-Based Management

With the increasing availability of reef resilience metrics, managers are faced with the challenge of incorporating this new information into existing frameworks and existing objectives for coral reef management and conservation. Resilience-Based Management presents a modified framework and process for incorporating these new perspectives (Anthony et al. 2015), but there is still substantial latitude for judgement in the process of objective setting and spatial prioritization.

Resilience Metric Performs Well Across Multiple Objectives

In our analysis, we have attempted to present a resilience assessment across a broad spatial scale, encompassing a diverse set of reef and social conditions and to rigorously and quantitatively evaluate the utility of a resilience metric to meet long-standing performance goals for a prioritized set of areas for focused management action.

The results of our performance metric comparisons and two-by-two efficiency frontiers show that in the central U.S. Pacific, our resilience metric performs well on a variety of objectives, including spatial representation, biodiversity representation, representation of socially vulnerable populations, and, if a large enough area is committed, protecting resource fish biomass. Of the six performance metrics examined, only protecting thermal refugia stood in direct tradeoff with a strategy that uses a multi-factor resilience metric to prioritize management action (Table 1).

Other Metrics Perform Poorly to Prioritize Resilience

In contrast, the five other prioritization strategies we tested failed to produce prioritized sets of areas with high resilience potential (Figure 9, Table 1). While *spatial representation* and *biodiversity* showed some potential to meet resilience goals, they both underperformed *resilience* when considering both metrics simultaneously (Figure 11, Figure 12).

Direct Trade-offs

Using the efficiency frontier plots as our guide (Figures 15−19), *thermal refugia* presents an apparently direct trade-off with *resilience* in that no proposed prioritization set from either strategy generates a substantive win-win outcome. Comparing their respective ranking maps (Figures 2−3) suggests that, though the remote islands in the PRIMNM are highly ranked for both, this difference between resilient and refuge areas is largely driven by the distinctions in the CNMI, with high resilience and low refugia potential, and NWHI, with low resilience and high refugia potential.

In considering this trade-off, it is worth considering the relatively small distinctions in the thermal refugia predictions. In the central Pacific, the range between the earliest and latest years to hit the onset of annual coral bleaching is 9 years (2036−2045), a value close to the level of error reported in the analysis (Van Hooidonk et al. 2016). This decade’s worth of difference is much smaller than the range reported in other regions and may make consideration of *thermal refugia* less of an issue in the central Pacific, especially if it lies in direct opposition to prioritizing resilience.

While much of our analysis is focused on the performance of our resilience metric relative to other strategies, the comparison also highlighted some clear trade-offs among other strategies. First, *social vulnerability* and *resource fish biomass* appear to be in direct opposition (Figure 6, Figure 7, Figure 13, Figure 14), as the reefs with the largest biomass of commercially important fishes are in remote, unpopulated or lightly populated areas with no social data. This trade-off continues between *social vulnerability* and *thermal refugia*, in that some reefs latest hit by warming (Van Hooidonk et al. 2016) occur in these same remote areas.

Blended Prioritization Strategies

While our resilience metric performs well across many scenarios, it is unlikely that it is the absolute best prioritization strategy for a given management objective; rather, managers are more liable to develop a blended strategy. Given our results, though, a resilience metric could form a core strategic part of any such blended strategy, and the performance assessment and efficiency frontier analysis demonstrated here can serve to evaluate the strengths, weaknesses, and required commitment levels for such a strategy.

Acknowledgements

The authors would like to acknowledge our funders at the NOAA Coral Reef Conservation Program and the support of our colleagues in the Ecosystem Science Division of NOAA's Pacific Islands Fisheries Science Center.

Literature Cited

Anderies JM, Walker BH, Kinzig AP. 2006. Fifteen Weddings and a Funeral: Case Studies and Resilience- based Management. Ecol Soc. 11:21. doi:21.

Anthony KRN, Marshall PA, Abdulla A, Beeden R, Bergh C, Black R, Eakin CM, Game ET, Gooch M, Graham NAJ, et al. 2015. Operationalizing resilience for adaptive coral reef management under global environmental change. Glob Chang Biol. 21:48–61. doi:10.1111/gcb.12700.

Brooks TM, Mittermeier RA, da Fonseca GAB, Gerlach J, Hoffmann M, Lamoreux JF, Mittermeier CG, Pilgrim JD, Rodrigues ASL. 2006. Global biodiversity conservation priorities. Science. 313:58–61.

Cinner JE, McClanahan TR, MacNeil MA, Graham NAJ, Daw TM, Mukminin A, Feary DA, Rabearisoa AL, Wamukota A, Jiddawi N, et al. 2012. Comanagement of coral reef social-ecological systems. Proc Natl Acad Sci. 109:5219–5222. doi:10.1073/pnas.1121215109.

Crowder L, Norse E. 2008. Essential ecological insights for marine ecosystem-based management and marine spatial planning. Mar policy. 32:772–778.

Game ET, Watts ME, Wooldridge S, Possingham HP. 2008. Planning for persistence in marine reserves: a question of catastrophic importance. Ecol Appl. 18:670–680.

Graham NAJ, Bellwood DR, Cinner JE, Hughes TP, Norström A V., Nyström M. 2013. Managing resilience to reverse phase shifts in coral reefs. Front Ecol Environ. 11:541–548. doi:10.1890/120305.

Groves CR, Game ET, Anderson MG, Cross M, Enquist C, Ferdaña Z, Girvetz E, Gondor A, Hall KR, Higgins J, et al. 2012. Incorporating climate change into systematic conservation planning. Biodivers Conserv. 21:1651–1671. doi:10.1007/s10531-012-0269-3.

Heron SF, Maynard JA, Van Hooidonk R, Eakin CM. 2016. Warming Trends and Bleaching Stress of the World's Coral Reefs 1985-2012. Sci Rep. 6:1–14. doi:10.1038/srep38402.

Hoegh-Guldberg O. 1998. Climate Change, coral bleaching and the future of the world's coral reefs. Ove Hoegh-Guldberg.

Van Hooidonk R, Maynard J, Tamelander J, Gove J, Ahmadia G, Raymundo L, Williams G, Heron SF, Planes S. 2016. Local-scale projections of coral reef futures and implications of the Paris Agreement. Sci Rep. 6:1–8. doi:10.1038/srep39666.

Jepson M, Colburn LL. 2013. Development of Social Indicators of Fishing Community Vulnerability and Resilience in the U.S. Southeast and Northeast Regions. NOAA Tech Memo NMFS-F/SPO-129.

Kleiber D, Kotowicz D, Hospital J. 2018. Applying National Community Social Vulnerability Indicators to Fishing Communities in the Pacific Island Region. doi:10.7289/V5/TM-PIFSC-65.

Kleypas JA, Buddemeier RW, Archer D, Gattuso JP, Langdon C, Opdyke BN. 1999. Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. Science. 284:118–120. doi:10.1126/science.284.5411.118.

Levin SA, Lubchenco J. 2008. Resilience , Robustness , and Marine Ecosystem-based Management. Bioscience. 58:27–32. doi:10.1641/B580107.

Maynard J, Mckagan S, Johnson S, Houk P. 2012. Coral reef resilience to climate change in Saipan , CNMI ; field-based assessments and implications for vulnerability and future management. :56.

Maynard JA, Marshall PA, Johnson JE, Harman S. 2010. Building resilience into practical conservation: Identifying local management responses to global climate change in the southern Great Barrier Reef. Coral Reefs. 29:381–391. doi:10.1007/s00338-010-0603-8.

Maynard JA, McKagan S, Raymundo L, Johnson S, Ahmadia GN, Johnston L, Houk P, Williams GJ, Kendall M, Heron SF, et al. 2015. Assessing relative resilience potential of coral reefs to inform management. Biol Conserv. 192:109–119. doi:10.1016/j.biocon.2015.09.001.

McClanahan TR, Donner SD, Maynard JA, MacNeil MA, Graham NAJ, Maina J, Baker AC, Alemu I. JB, Beger M, Campbell SJ, et al. 2012. Prioritizing Key Resilience Indicators to Support Coral Reef Management in a Changing Climate. PLoS One. 7. doi:10.1371/journal.pone.0042884.

McLeod E, Green A, Game E, Anthony K, Cinner J, Heron SF, Kleypas J, Lovelock CE, Pandolfi JM, Pressey RL, et al. 2012. Integrating Climate and Ocean Change Vulnerability into Conservation Planning. Coast Manag. 40:651–672. doi:10.1080/08920753.2012.728123.

Mumby PJ, Wolff NH, Bozec YM, Chollett I, Halloran P. 2014. Operationalizing the resilience of coral reefs in an era of climate change. Conserv Lett. 7:176–187. doi:10.1111/conl.12047.

Obura D, Grimsditch G. 2009. Resilience Assessment of Coral Reefs bleaching and thermal stress.

Roberts CM, McClean CJ, Veron JEN, Hawkins JP, Allen GR, McAllister DE, Mittermeier CG, Schueler FW, Spalding M, Wells F, et al. 2002. Marine biodiversity hotspots and conservation priorities for tropical reefs. Science 295:1280–1284.

West JM, Ph D, Salm R V. 2003. Resistance and resilience to coral bleaching: implications for coral reef conservation and management. Conserv Biol. 17:956–967.

White C, Halpern BS, Kappel C V. 2012. Ecosystem service tradeoff analysis reveals the value of marine spatial planning for multiple ocean uses. Proc Natl Acad Sci. 109:4696–4701. doi:10.1073/pnas.1114215109.

Williams ID, Baum JK, Heenan A, Hanson KM, Nadon MO, Brainard RE. 2015. Human, Oceanographic and Habitat Drivers of Central and Western Pacific Coral Reef Fish Assemblages. PLoS One. 10:e0120516. doi:10.1371/journal.pone.0120516.

Appendix A: Coral Canonical Species Table

Field identification of coral taxa to species in some cases is difficult and unreliable. What follows below is the table describing which taxa we id to species, and which to genus.

Species code	**Genus**	**Species Name**	**Rank**
AABR	*Acropora*	*Acropora abrotanoides*	SPECIES
AASP	*Acropora*	*Acropora aspera*	SPECIES
ACAS	*Acanthastrea*	*Acanthastrea* sp.	GENUS
ACSP	*Acropora*	*Acropora* sp.	GENUS
ACYT	*Acropora*	*Acropora cytherea*	SPECIES
AHEM	*Acanthastrea*	*Acanthastrea hemprichii*	SPECIES
AHUM	*Acropora*	*Acropora humilis*	SPECIES
AHYA	*Acropora*	*Acropora hyacinthus*	SPECIES
AISH	*Acanthastrea*	*Acanthastrea ishigakiensis*	SPECIES
ALSP	*Alveopora*	*Alveopora* sp.	GENUS
ALVE	*Alveopora*	*Alveopora verrilliana*	SPECIES
AMIC	*Acropora*	*Acropora microclados*	SPECIES
AMYR	*Astreopora*	*Astreopora myriophthalma*	SPECIES
ANAS	*Acropora*	*Acropora nasuta*	SPECIES
ANOB	*Acropora*	*Acropora nobilis*	SPECIES
APAN	*Acropora*	*Acropora paniculata*	SPECIES
ASPE	*Acropora*	*Acropora speciosa*	SPECIES
ASSP	*Astreopora*	*Astreopora* sp.	GENUS
AVAL	*Acropora*	*Acropora valida*	SPECIES
AVER	*Acropora*	*Acropora verweyi*	SPECIES
BARS	*Barabattoia*	*Barabattoia* sp.	GENUS
CASP	*Caulastrea*	*Caulastrea* sp.	GENUS
CCOL	*Coscinaraea*	*Coscinaraea columna*	SPECIES
CEXE	*Coscinarea*	*Coscinarea exesa*	SPECIES
CMAY	*Coeloseris*	*Coeloseris mayeri*	SPECIES
COCE	*Cyphastrea*	*Cyphastrea ocellina*	SPECIES
COES	*Coeloseris*	*Coeloseris* sp.	GENUS
COSP	*Coscinaraea*	*Coscinaraea* sp.	GENUS
CTSP	*Ctenactis*	*Ctenactis* sp.	GENUS
CYPS	*Cyphastrea*	*Cyphastrea* sp.	GENUS
CYSP	*Cycloseris*	*Cycloseris* sp.	GENUS
DHEL	*Diploastrea*	*Diploastrea heliopora*	SPECIES
DIAS	*Diaseris*	*Diaseris* sp.	GENUS
DISP	*Diaseria*	*Diaseria* sp.	GENUS
ECHL	*Echinophyllia*	*Echinophyllia* sp.	GENUS

Species code	Genus	Species Name	Rank
ECHP	*Echinopora*	*Echinopora* sp.	GENUS
EGEM	*Echinopora*	*Echinopora gemmacea*	SPECIES
ELAM	*Echinopora*	*Echinopora lamellosa*	SPECIES
EUSP	*Euphyllia*	*Euphyllia* sp.	GENUS
FASP	*Favia*	*Favia* sp.	GENUS
FAVS	*Favites*	*Favites* sp.	GENUS
FGRA	*Fungia*	*Fungia granulosa*	SPECIES
FMAT	*Favia*	*Favia matthaii*	SPECIES
FSCU	*Fungia*	*Fungia scutaria*	SPECIES
FSTE	*Favia*	*Favia stelligera*	SPECIES
FUSP	*Fungia*	*Fungia* sp.	GENUS
GAAS	*Galaxea*	*Galaxea astreata*	SPECIES
GARS	*Gardineroseris*	Gardineroseris sp.	GENUS
GASP	*Galaxea*	*Galaxea* sp.	GENUS
GEDW	*Goniastrea*	*Goniastrea edwardsi*	SPECIES
GFAS	*Galaxea*	*Galaxea fascicularis*	SPECIES
GONS	*Goniastrea*	*Goniastrea* sp.	GENUS
GOSP	*Goniopora*	*Goniopora* sp.	GENUS
GPEC	*Goniastrea*	*Goniastrea pectinata*	SPECIES
GPLA	*Gardineroseris*	*Gardineroseris planulata*	SPECIES
GRET	*Goniastrea*	*Goniastrea retiformis*	SPECIES
HASP	*Halomitra*	*Halomitra* sp.	GENUS
HCOE	*Heliopora*	*Heliopora coerula*	SPECIES
HERS	*Herpolitha*	*Herpolitha* sp.	GENUS
HESP	*Heliopora*	*Heliopora* sp.	GENUS
HEXE	*Hydnophora*	*Hydnophora exesa*	SPECIES
HMIC	*Hydnophora*	*Hydnophora microconnos*	SPECIES
HRIG	*Hydnophora*	*Hydnophora rigida*	SPECIES
HYSP	*Hydnophora*	*Hydnophora* sp.	GENUS
ISSP	*Isopora*	*Isopora* sp.	GENUS
LBEW	*Leptastrea*	*Leptastrea bewickensis*	SPECIES
LEPS	*Leptoria*	*Leptoria* sp.	GENUS
LEPT	*Leptastrea*	*Leptastrea* sp.	GENUS
LESP	*Leptoseris*	*Leptoseris* sp.	GENUS
LINC	*Leptoseris*	*Leptoseris incrustans*	SPECIES
LMYC	*Leptoseris*	*Leptoseris myceteroides*	SPECIES
LOBS	*Lobophyllia*	*Lobophyllia* sp.	GENUS
LPHY	*Leptoria*	*Leptoria phyrgia*	SPECIES
LPRU	*Leptastrea*	*Leptastrea pruinosa*	SPECIES

Species code	Genus	Species Name	Rank
LPUR	*Leptastrea*	*Leptastrea pupurea*	SPECIES
LTRA	*Leptastrea*	*Leptastrea transversa*	SPECIES
MAMP	*Merulina*	*Merulina ampliata*	SPECIES
MCAL	*Montipora*	*Montipora caliculata*	SPECIES
MCAP	*Montipora*	*Montipora capitata*	SPECIES
MCUR	*Montastraea*	*Montastraea curta*	SPECIES
MDIL	*Montipora*	*Montipora dilatata*	SPECIES
MESP	*Merulina*	*Merulina* sp.	GENUS
MFLA	*Montipora*	*Montipora flabellata*	SPECIES
MINC	*Montipora*	*Montipora incrassata*	SPECIES
MISP	*Millepora*	*Millepora* sp.	GENUS
MONS	*Montastraea*	*Montastraea* sp.	GENUS
MOSP	*Montipora*	*Montipora* sp.	GENUS
MPAT	*Montipora*	*Montipora patula*	SPECIES
MSCA	*Merulina*	*Merulina scabricula*	SPECIES
MTUR	*Montipora*	*Montipora turgescens*	SPECIES
MVAL	*Montastraea*	*Montastraea valenciennesi*	SPECIES
MYSP	*Mycedium*	*Mycedium* sp.	GENUS
OUSP	*Oulophyllia*	*Oulophyllia* sp.	GENUS
OXSP	*Oxypora*	*Oxypora* sp.	GENUS
PACS	*Pachyseris*	*Pachyseris* sp.	GENUS
PANN	*Porites*	*Porites cf. annae*	SPECIES
PAVS	*Pavona*	*Pavona* sp.	GENUS
PBER	*Porites*	*Porites bernardi*	SPECIES
PBRI	*Porites*	*Porites brighami*	SPECIES
PCAP	*Pocillopora*	*Pocillopora capitata*	SPECIES
PCHI	*Pavona*	*Pavona cf chiriquiensis*	SPECIES
PCOM	*Porites*	*Porites compressa*	SPECIES
PCYL	*Porites*	*Porites cylindrica*	SPECIES
PDAM	*Pocillopora*	*Pocillopora damicornis*	SPECIES
PDAN	*Pocillopora*	*Pocillopora danae*	SPECIES
PDIF	*Pavona*	*Pavona diffluens*	SPECIES
PDUE	*Pavona*	*Pavona duerdeni*	SPECIES
PESP	*Pectinia*	*Pectinia* sp.	GENUS
PEVE	*Porites*	*Porites evermanni*	SPECIES
PEYD	*Pocillopora*	*Pocillopora eydouxi*	SPECIES
PHAI	*Psammocora*	*Psammocora haimeana*	SPECIES
PHOR	*Porites*	*Porites horizontalata*	SPECIES
PLDA	*Platygyra*	*Platygyra daedalea*	SPECIES

Species code	Genus	Species Name	Rank
PLER	*Plerogyra*	*Plerogyra* sp.	GENUS
PLES	*Plesiastrea*	*Plesiastrea* sp.	GENUS
PLIC	*Porites*	*Porites lichen*	SPECIES
PLIG	*Pocillopora*	*Pocillopora ligulata*	SPECIES
PLOB	*Porites*	*Porites lobata*	SPECIES
PLSP	*Platygyra*	*Platygyra* sp.	GENUS
PLUT	*Porites*	*Porites lutea*	SPECIES
PLVE	*Plesiastrea*	*Plesiastrea versipora*	SPECIES
PMAL	*Pavona*	*Pavona maldivensis*	SPECIES
PMEA	*Pocillopora*	*Pocillopora meandrina*	SPECIES
PMOL	*Pocillopora*	*Pocillopora molokensis*	SPECIES
PMON	*Porites*	*Porites monticulosa*	SPECIES
PNIE	*Psammocora*	*Psammocora nierstraszi*	SPECIES
POCS	*Pocillopora*	*Pocillopora* sp.	GENUS
PODS	*Podabacia*	*Podabacia* sp.	GENUS
PODU	*Porites*	*Porites duerdeni*	SPECIES
POLY	*Polyphyllia*	*Polyphyllia* sp.	GENUS
POSP	*Porites*	*Porites* sp.	GENUS
PPIN	*Platygyra*	*Platygyra pini*	SPECIES
PRUG	*Pachyseris*	*Pachyseris rugosa*	SPECIES
PRUS	*Porites*	*Porites rus*	SPECIES
PSET	*Pocillopora*	*Pocillopora setchelli*	SPECIES
PSOL	*Porites*	*Porites solida*	SPECIES
PSSP	*Psammocora*	*Psammocora* sp.	GENUS
PSTE	*Psammocora*	*Psammocora stellata*	SPECIES
PVAR	*Pavona*	*Pavona varians*	SPECIES
PVEN	*Pavona*	*Pavona venosa*	SPECIES
PWOO	*Pocillopora*	*Pocillopora woodjonesi*	SPECIES
SASP	*Sandalolitha*	*Sandalolitha* sp.	GENUS
SCAS	*Scapophyllia*	*Scapophyllia* sp.	GENUS
SCSP	*Scolymia*	*Scolymia* sp.	GENUS
SCYL	*Scapophyllia*	*Scapophyllia cylindrica*	SPECIES
SESP	*Seriatopora*	*Seriatopora* sp.	GENUS
SPIS	*Stylophora*	*Stylophora pistillata*	SPECIES
STSP	*Stylocoeniella*	*Stylocoeniella* sp.	GENUS
STYP	*Stylaraea*	*Stylaraea* sp.	GENUS
STYS	*Stylophora*	*Stylophora* sp.	GENUS
SYSP	*Symphyllia*	*Symphyllia* sp.	GENUS
TMES	*Turbinaria*	*Turbinaria mesenterina*	SPECIES

Species code	Genus	Species Name	Rank
TPEL	*Turbinaria*	*Turbinaria peltata*	SPECIES
TREN	*Turbinaria*	*Turbinaria reniformis*	SPECIES
TSTE	*Turbinaria*	*Turbinaria stellulata*	SPECIES
TURS	*Turbinaria*	*Turbinaria* sp.	GENUS
TUSP	*Tubastrea*	*Tubastrea* sp.	GENUS

Appendix B: Resource Fish Table

All listed species are included as resource fish. These fishes have LMAX ≥40 cm for most families (emperors, grouper, parrotfish, jacks, squirrelfish, tuna, goatfish, snapper), PLUS all surgeonfishes with LMAX ≥30 cm. Lmax is the species maximum size.

Species	Taxon	Family	Common Family	Consumer Group	Lmax (cm)
SURG	Acanthuridae	Acanthuridae	Surgeonfish	PRIMARY	70
ACAL	*Acanthurus albipectoralis*	Acanthuridae	Surgeonfish	PRIMARY	33
ACBL	*Acanthurus blochii*	Acanthuridae	Surgeonfish	PRIMARY	43
ACDU	*Acanthurus dussumieri*	Acanthuridae	Surgeonfish	PRIMARY	56
ACLU	*Acanthurus leucocheilus*	Acanthuridae	Surgeonfish	PRIMARY	45
ACLI	*Acanthurus lineatus*	Acanthuridae	Surgeonfish	PRIMARY	38
ACMA	*Acanthurus maculiceps*	Acanthuridae	Surgeonfish	PRIMARY	41
ACMT	*Acanthurus mata*	Acanthuridae	Surgeonfish	PLANKTIVORE	50
ACNI	*Acanthurus nigricauda*	Acanthuridae	Surgeonfish	PRIMARY	40
ACOL	*Acanthurus olivaceus*	Acanthuridae	Surgeonfish	PRIMARY	40
ACSP	*Acanthurus* sp.	Acanthuridae	Surgeonfish	PRIMARY	57
ACXA	*Acanthurus xanthopterus*	Acanthuridae	Surgeonfish	PRIMARY	65
NAAN	*Naso annulatus*	Acanthuridae	Surgeonfish	PLANKTIVORE	100
NABH	*Naso brachycentron*	Acanthuridae	Surgeonfish	PRIMARY	90
NABR	*Naso brevirostris*	Acanthuridae	Surgeonfish	PLANKTIVORE	60
NAHE	*Naso hexacanthus*	Acanthuridae	Surgeonfish	PLANKTIVORE	75
NALI	*Naso lituratus*	Acanthuridae	Surgeonfish	PRIMARY	46
NASP	*Naso* sp.	Acanthuridae	Surgeonfish	PLANKTIVORE	75
NATO	*Naso tonganus*	Acanthuridae	Surgeonfish	PRIMARY	63
NAUN	*Naso unicornis*	Acanthuridae	Surgeonfish	PRIMARY	70
NAVL	*Naso vlamingii*	Acanthuridae	Surgeonfish	PLANKTIVORE	60
PAHP	*Paracanthurus hepatus*	Acanthuridae	Surgeonfish	PLANKTIVORE	31
ZEVE	*Zebrasoma veliferum*	Acanthuridae	Surgeonfish	PRIMARY	40
ALCI	*Alectis ciliaris*	Carangidae	Jack	PISCIVORE	150
JACK	Carangidae	Carangidae	Jack	PISCIVORE	160
CAFE	*Carangoides ferdau*	Carangidae	Jack	PISCIVORE	70
CAOR	*Carangoides orthogrammus*	Carangidae	Jack	PISCIVORE	70
CAIG	*Caranx ignobilis*	Carangidae	Jack	PISCIVORE	165
CALU	*Caranx lugubris*	Carangidae	Jack	PISCIVORE	100
CAME	*Caranx melampygus*	Carangidae	Jack	PISCIVORE	117
CASE	*Caranx sexfasciatus*	Carangidae	Jack	PISCIVORE	100
ELBI	*Elagatis bipinnulata*	Carangidae	Jack	PISCIVORE	180
PSDE	*Pseudocaranx dentex*	Carangidae	Jack	PISCIVORE	122
SCLY	*Scomberoides lysan*	Carangidae	Jack	PISCIVORE	70

Species	Taxon	Family	Common Family	Consumer Group	Lmax (cm)
SEDU	*Seriola dumerili*	Carangidae	Jack	PISCIVORE	190
TRBA	*Trachinotus baillonii*	Carangidae	Jack	PISCIVORE	54
TRBL	*Trachinotus blochii*	Carangidae	Jack	SECONDARY	110
MYMU	*Myripristis murdjan*	Holocentridae	Soldierfish	PLANKTIVORE	60
SAPP	*Sargocentron* sp.	Holocentridae	Soldierfish	SECONDARY	50
SASP	*Sargocentron spiniferum*	Holocentridae	Soldierfish	SECONDARY	52
EMPE	Lethrinidae	Lethrinidae	Emperor	SECONDARY	86
LEAM	*Lethrinus amboinensis*	Lethrinidae	Emperor	SECONDARY	70
LEER	*Lethrinus erythracanthus*	Lethrinidae	Emperor	SECONDARY	70
LEOB	*Lethrinus obsoletus*	Lethrinidae	Emperor	SECONDARY	50
LEOL	*Lethrinus olivaceus*	Lethrinidae	Emperor	PISCIVORE	100
LETH	*Lethrinus* sp.	Lethrinidae	Emperor	SECONDARY	86
LEXA	*Lethrinus xanthochilus*	Lethrinidae	Emperor	PISCIVORE	62
MOGR	*Monotaxis grandoculis*	Lethrinidae	Emperor	SECONDARY	63
APFU	*Aphareus furca*	Lutjanidae	Snapper	PISCIVORE	70
APVI	*Aprion virescens*	Lutjanidae	Snapper	PISCIVORE	112
LUBO	*Lutjanus bohar*	Lutjanidae	Snapper	PISCIVORE	90
LUGI	*Lutjanus gibbus*	Lutjanidae	Snapper	SECONDARY	53
LUMO	*Lutjanus monostigma*	Lutjanidae	Snapper	PISCIVORE	60
MAMA	*Macolor macularis*	Lutjanidae	Snapper	PLANKTIVORE	60
MANI	*Macolor niger*	Lutjanidae	Snapper	PLANKTIVORE	75
GOAT	Mullidae	Mullidae	Goatfish	SECONDARY	50
MUPF	*Mulloidichthys pfluegeri*	Mullidae	Goatfish	SECONDARY	48
PABA	*Parupeneus barberinus*	Mullidae	Goatfish	SECONDARY	50
PACY	*Parupeneus cyclostomus*	Mullidae	Goatfish	PISCIVORE	50
PAPO	*Parupeneus porphyreus*	Mullidae	Goatfish	SECONDARY	51
CACA	*Calotomus carolinus*	Scaridae	Parrotfish	PRIMARY	54
CEOC	*Cetoscarus ocellatus*	Scaridae	Parrotfish	PRIMARY	90
CHFN	*Chlorurus frontalis*	Scaridae	Parrotfish	PRIMARY	50
CHMC	*Chlorurus microrhinos*	Scaridae	Parrotfish	PRIMARY	80
CHPE	*Chlorurus perspicillatus*	Scaridae	Parrotfish	PRIMARY	62
HILO	*Hipposcarus longiceps*	Scaridae	Parrotfish	PRIMARY	60
PARR	Scaridae	Scaridae	Parrotfish	PRIMARY	68
SCAL	*Scarus altipinnis*	Scaridae	Parrotfish	PRIMARY	60
SCFE	*Scarus festivus*	Scaridae	Parrotfish	PRIMARY	45
SCFO	*Scarus forsteni*	Scaridae	Parrotfish	PRIMARY	55
SCFR	*Scarus frenatus*	Scaridae	Parrotfish	PRIMARY	47
SCGH	*Scarus ghobban*	Scaridae	Parrotfish	PRIMARY	90
SCNI	*Scarus niger*	Scaridae	Parrotfish	PRIMARY	43

Species	Taxon	Family	Common Family	Consumer Group	Lmax (cm)
SCRU	*Scarus rubroviolaceus*	Scaridae	Parrotfish	PRIMARY	70
SCSP	*Scarus* sp.	Scaridae	Parrotfish	PRIMARY	130
SCTR	*Scarus tricolor*	Scaridae	Parrotfish	PRIMARY	55
EUAF	*Euthynnus affinis*	Scombridae	Tuna	PISCIVORE	100
GYUC	*Gymnosarda unicolor*	Scombridae	Tuna	PISCIVORE	248
SAOR	*Sarda orientalis*	Scombridae	Tuna	PISCIVORE	102
TUNA	Scombridae	Scombridae	Tuna	PISCIVORE	245
AERO	*Aethaloperca rogaa*	Serranidae	Grouper	PISCIVORE	60
ANLE	*Anyperodon leucogrammicus*	Serranidae	Grouper	PISCIVORE	60
CEAR	*Cephalopholis argus*	Serranidae	Grouper	PISCIVORE	60
CEMI	*Cephalopholis miniata*	Serranidae	Grouper	PISCIVORE	45
CESX	*Cephalopholis sexmaculata*	Serranidae	Grouper	PISCIVORE	50
CESO	*Cephalopholis sonnerati*	Serranidae	Grouper	PISCIVORE	50
EPFA	*Epinephelus fasciatus*	Serranidae	Grouper	PISCIVORE	43
EPHO	*Epinephelus howlandi*	Serranidae	Grouper	PISCIVORE	55
EPMC	*Epinephelus macrospilos*	Serranidae	Grouper	PISCIVORE	51
EPMA	*Epinephelus maculatus*	Serranidae	Grouper	PISCIVORE	60
EPPO	*Epinephelus polyphekadion*	Serranidae	Grouper	PISCIVORE	75
EPRE	*Epinephelus retouti*	Serranidae	Grouper	PISCIVORE	47
EPSP	*Epinephelus* sp.	Serranidae	Grouper	PISCIVORE	128
EPTA	*Epinephelus tauvina*	Serranidae	Grouper	PISCIVORE	75
GRAL	*Gracila albomarginata*	Serranidae	Grouper	PISCIVORE	50
PLLV	*Plectropomus laevis*	Serranidae	Grouper	PISCIVORE	125
GROU	Serranidae	Serranidae	Grouper	PISCIVORE	128
VAAL	*Variola albimarginata*	Serranidae	Grouper	PISCIVORE	65
VALO	*Variola louti*	Serranidae	Grouper	PISCIVORE	83