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WESTERN PACIFIC REGIONAL FISHERY MANAGEMENT COUNCIL

IMPROVING SPECIFICATION OF ACCEPTABLE BIOLOGICAL CATCHES OF DATA-POOR REEF FISH STOCKS USING A BIOMASS-AUGMENTED CATCH-MSY APPROACH

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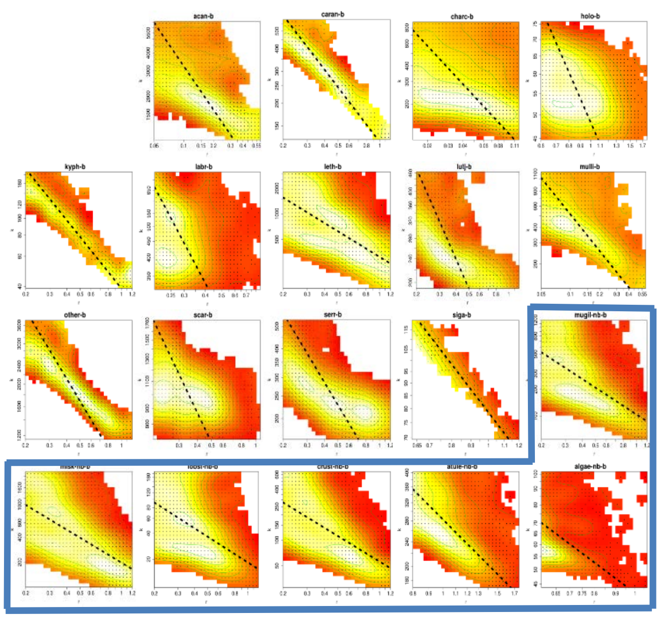

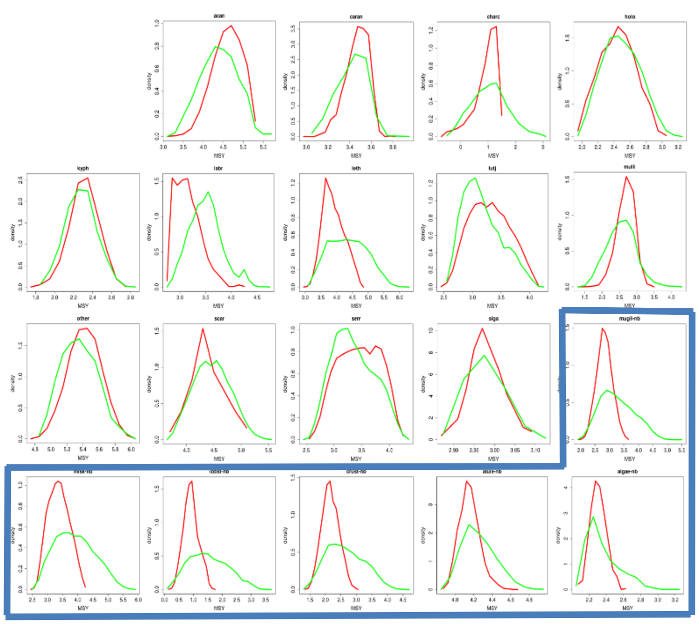

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ABSTRACT

The coral reef fisheries in the Western Pacific region has been in existence for more than 3 millennia and had supported the indigenous people of American Samoa, Guam, Commonwealth of Northern Mariana Island and Hawaii to the present day. Productivity of the coral reefs is generally perceived to be declining over the past century due to various compounding factors interacting with the reef fish stocks. Management of these stocks could employ various fishery management tools ranging from gear restriction to spatial management. Annual catch limits had been required in 2006 as the tool to end overfishing in the federal fisheries in the United States. The starting point of this management regime is to determine the overfishing limits or proxies such as a maximum sustainable yield usually generated through a stock assessment. Stock assessments of reef fishes are virtually non-existent in the Western Pacific region thereby deeming the reef fish stock in a data-poor situation. Various data-poor approaches were available but produce limits that are overly restrictive. A modified Bayesian modeling approach based on Martell and Froese (2012) was developed to enhance the catch limit specification for reef fishes. An estimate of the maximum sustainable yield was generated from catch time series, a measure of rate of population growth *r*, carrying capacity *k*, and biomass from underwater fish census surveys.

INTRODUCTION

Fishing on coral reefs in the Western Pacific region has been practiced by the indigenous people of American Samoa, Guam, Commonwealth of the Northern Mariana Islands, and Hawaii for more than 3 millennia (Dye and Graham 2004). This practice has been embedded in the fabric of their culture and tradition despite changes in the socio-economic and socio-cultural setting brought about by urbanization and western influence (Allen and Amesbury 2012; Levine and Sauafea-Leau 2013). In the age of globalization and modernization, the coral reef and associated fisheries are being threatened from multiple fronts and scales: land-based pollution resulting on phase shifts (Pastorok and Bilyard 1985; Hughes 1994; Edinger et al. 1998), global warming coupled with climate change (Brander 2007; Munday et al. 2008), and destructive fishing coupled with overexploitation (Edinger et al. 1998; Jackson et al. 2001; Newton et al. 2007; McClanahan et al. 2008) etc. The multidimensionality of the coral reef fisheries pose a significant challenge to management hence multiple tools had been developed to address various impacts affecting the fisheries. These management tools range from spatial-temporal management like rotational closures or permanents no-take marine protected areas (Roberts and Polunin 1993) and/or the traditional fishery tools like input controls (e.g. gear restriction, limited entry program, effort limits) and output controls (e.g. size limits, bag limits, seasonal closures and catch limits) . All these tools are geared towards conserving and managing stocks that are regarded to be in decline on a regional and global scale (Pandolfi et al 2003; Newton et al 2007; Zeller et al. 2007; Worm et al. 2009).

The application of these diverse fishery management tools would depend on the long term goal for the stocks. The re-authorization of the Magnuson-Stevens Fishery Conservation and Management Act in 2007 required the implementation of annual catch limits for the different fisheries in the United States and its territories with an overall goal of preventing overfishing at the same time develop fisheries that are underutilized or not utilized to assure that the citizens benefit from employment, food supply and revenue which could be generated thereby. It is therefore inherent that in order to provide sustainable economic benefit to the nation, the fishery stocks should be sustainable on a long-term.

However, what makes sense on a national level may not necessarily apply on a regional scale given the diversity of culture, fishing practices, and the fish stocks being managed. The U.S federal waters in the western Pacific Ocean are managed by the Western Pacific Regional Fishery Management Council. This region is comprised of the Pacific Remote Island Areas consisting of small island and atolls of Palmyra, Jarvis, Johnston, Wake, Howland and Baker, the State of Hawaii, the Commonwealth of Northern Mariana Islands, Guam, and American Samoa at the southern hemisphere (Figure 1). This Council manages hundreds of marine species through its Fishery Ecosystem Plans including corals and coral reef fishes. The scientific information for each stock and fishery varies. In order to comply with the requirements of the Magnuson-Steven Act in ending overfishing and the National Standard 1 (implementing guidelines on annual catch limits specification), the Council developed an amendment to the Pacific Remote Island Areas (PRIAs), American Samoa, Marianas, and Hawaii FEPs to include a tier system of control rules in specifying Acceptable Biological Catches and a set of options for specifying annual catch limits below the acceptable biological catches (WPRFMC 2011). The tiers ranged from Tier 1 stocks with the best quality information (i.e., typically with a stock assessment and an estimated risk of overfishing), to Tier 5 (i.e., stocks with only catch information available). The majority of the coral reef fish stocks have been categorized as Tier 5. Conventional stock assessment is impractical for many coral reef stocks due to the number of species, limited life history information and multiple gears that harvest various subsets of the stocks at one time. Therefore, not only are coral reef fish stocks data-poor but also managing coral reef fisheries on a stock basis poses a management challenge.

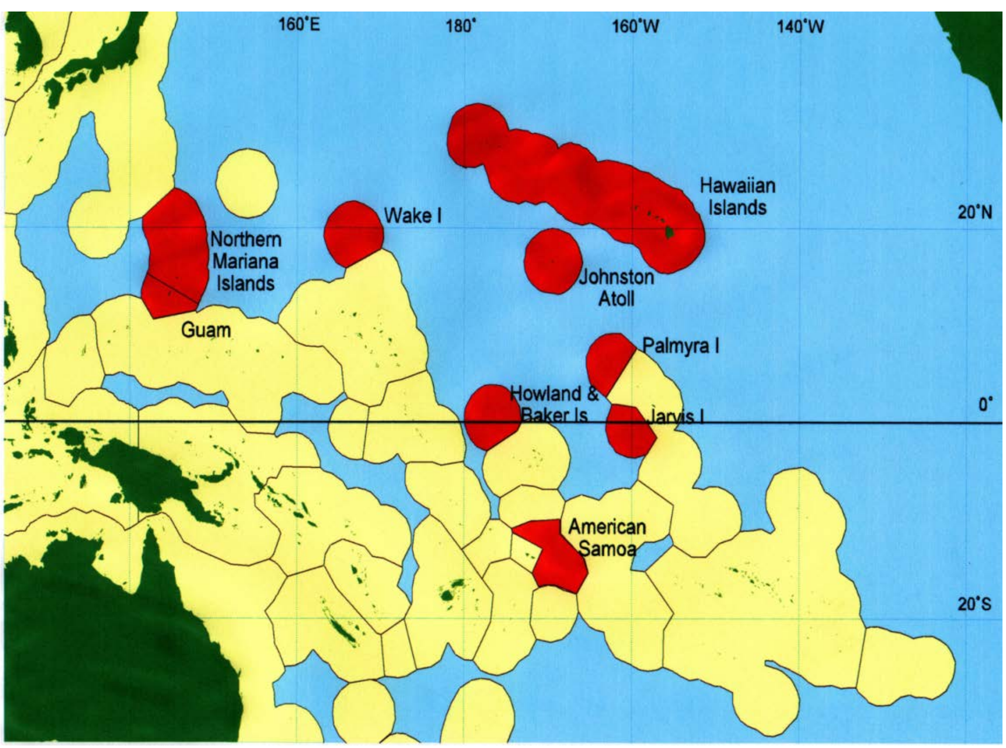

Figure 1. Map of the Western Pacific region showing the Exclusive Economic Zones (EEZs). The red EEZs (3-200 nm) are under the fishery management jurisdiction of the Western Pacific Regional Fishery Management Council.

PROBLEMS WITH ANNUAL CATCH LIMIT SPECIFICATION FOR DATA-POOR STOCKS

The most critical requirement of a successful catch-limit based management is a knowing the status of the stock. This is usually generated from stock assessments that are non-existent in the Western Pacific region. The starting point for the annual catch limit specification process is the estimation of the maximum fishing mortality threshold. This is the level of fishing mortality, on an annual basis, above which overfishing is occurring. The annual catch associated with this fishing mortality corresponds to the overfishing limit. These parameters cannot be estimated if an assessment is not done for the species being subject to this type of management measure. In the absence of a stock assessment, the specification process becomes subjective and precautionary principle dictates that management should err to the side of caution therefore forces manager to be extremely conservative. For the coral reef fish stocks, there were no estimated overfishing limits and the acceptable biological catches and annual catch limits were based purely on catch data.

The initial Tier 5 acceptable biological catch specifications for the coral reef ecosystem MUS in the Western Pacific Region was based on the guideline suggested by Restrepo et al. (1998) where the catch limit is set equal to, or a fraction of, the long-term average of reliable annual catch from a period in the fishery when there was no quantitative or qualitative evidence of declining abundance. However, the catch trends in the coral reef fishery did not exhibit a time period with little or no decline for most of the reef fish families (Figure 2). Coral reef fish species were categorized to the family level because species level catch information was not available for most of the areas given the way the data collection had been designed. Given the large fluctuations in catch, the Council utilized the entire catch time series (American Samoa: 1990 to 2008; Guam: 1985 to 2008; CNMI: 2000 to 2008; Hawaii: 1948 to 2007) from creel surveys in the Territories and fisherman's trip report from the State of Hawaii. Catch data from creel surveys are not quite reliable because it does not provide an estimate of total catch. The fisherman trip reporting system also does not provide an estimate of total catch because this is only focused on commercial landings. Despite the under estimation of total catch, these were the readily available sources of catch information that can be used for management.

The Council chose the acceptable biological catches equal to the 75th percentile of historic catches rather than the long-term median. This would provide a non-parametric approach and three out of four chances of catches being below the potential limit at any given year. The annual catch limit was set equal to acceptable biological catch since there were indications from the biomass estimates that catches were a relatively small portion of corresponding biomass (Luck and Dalzell 2010, Sabater and Tulafono 2011). There are indications that the coral reef fisheries in some parts of the Western Pacific region might be sustainable based on a comprehensive analysis using fishery dependent, fishery independent, archaeological and socioeconomic information (Sabater and Carroll 2009). This is contrary to the general notion of the major decline in productivity based solely on either biomass or catch information (Williams et al. 2011, Newton et al. 2007, Zeller et al. 2007, Houk et al. 2012).

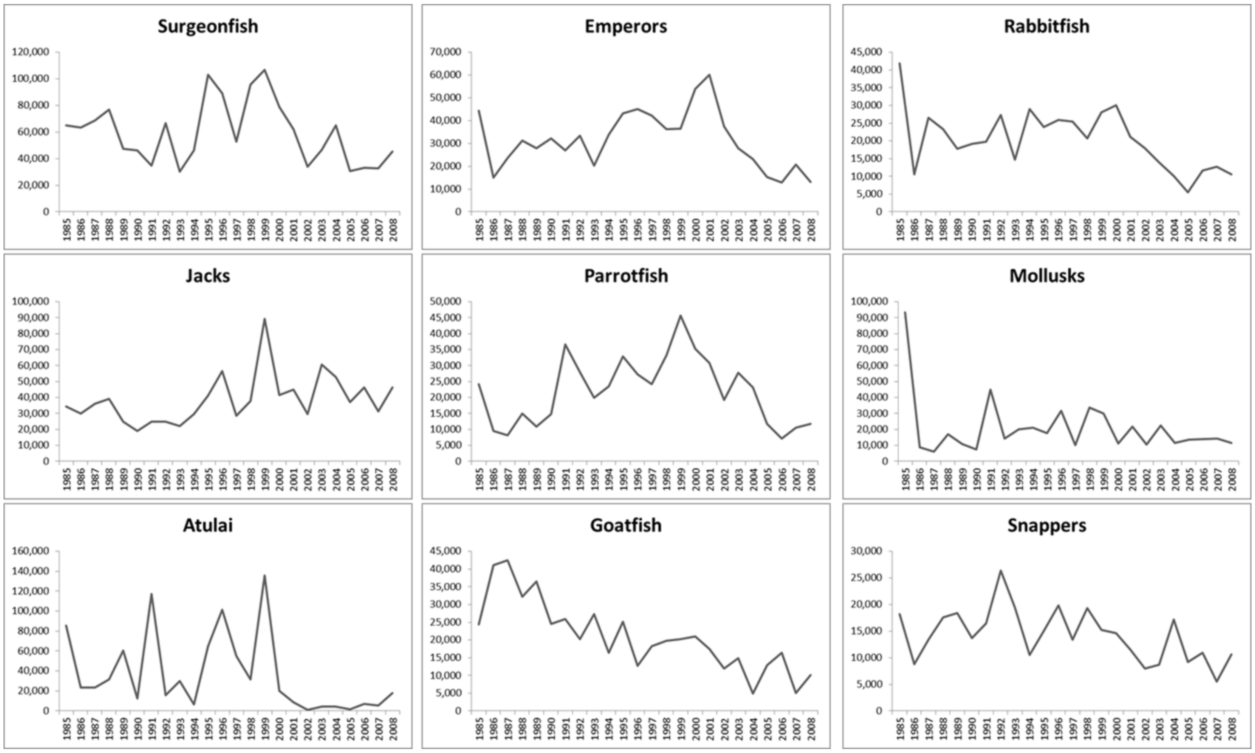

Figure 2. Sample coral reef fish catch time series from Guam indicating inter-annual fluctuation in catch from 1985 to 2008. Y-axes are catch landings in pounds while the X-axes are in years.

The initial annual catch limits specification were solely based on catch information and does not directly incorporate biomass information or other relevant data in the calculations. Some of the initial harvest limits were also very restrictive since they were based only on creel surveys, which even when expanded represented only a portion of total catch. Some of the fisheries, particularly the night-time spearfishing, are inadequately documented in creel surveys and are better represented by the commercial receipt-book data. The underestimation in the reported catches was estimated at between 2.2, 2.5 and 7 fold for the Commonwealth of Northern Mariana Islands (CNMI), Guam and American Samoa, respectively (Zeller et al. 2007). Given the severe underestimation resulting in an overly restrictive annual catch limits, the Council is shifting to a model-based approach in specifying acceptable biological catches which would incorporate biomass information and other life history traits to augment the limitations of catch-only information.

In addition, the way the Tier 5 control rule had been implemented generated an unforeseen and unintentional “ratchet-down” effect. Utilizing the entire catch time series in calculating for the annual catch limits required the Council to add the most recent data once it is available as mandated by NMFS National Standard 2 (use of the best scientific information available). Over the long-term implementation of the catch limits and the fishery is in compliant keeping the catch below the specified limits, this will result in a “ratchet-down” effect once new data are added in the time series when calculating for new annual catch limits. Conversely, if the fishery is not-compliant and the catches are consistently above the 75th percentile, application of the control rule would cause the acceptable biological catch to increase over time creating a disincentive to comply with the limits.

MOVING FROM DATA-POOR TIER TO MODEL-BASED TIER

Biomass, abundance, species composition, average length, coral reef habitat, qualitative estimate of natural mortality and limited fishing mortality and life history information are available for the coral reef species in the Western Pacific region. All these information needs to be utilized in order to move the coral reef stocks from the data-poor tier (Tier 5) applies only catch information to Tier 3 that generates an estimate of sustainable harvest levels through model-based approaches. Four models were explored to enhance the annual catch limit specification process. These were: 1) a bulk estimator of Maximum Sustainable Yield (MSY) using modified Schaefer and Fox model (Garcia et al. 1989); 2) depletion-corrected average catches (DCAC) (MacCall 2009); 3) depletion-based stock reduction analysis (DB-SRA) (Dick and MacCall 2011); and 4) catch-MSY estimator (Martell and Froese 2012).

The Garcia et al. (1989) bulk estimator generates a point estimate of MSY from straightforward derivations of two well-known surplus production models (Schaefer 1954; Fox 1970). These equations are suitable for the certain cases where no available long time series of catch or effort and where the only estimates available are the total catch, average total biomass and an expert guess of fishing mortality needed to obtain the MSY of the fish stocks in question. These equations have similar limitations and constraints as the models from which they were derived. The main assumptions were that the biological processes involved are deterministic, the fishery is on a single stock with stable age/size characteristics, the catchability is not density-dependent, and there are no time lags between catch and productivity. Using this model would be challenging due to its applicability to a complex fishery like the coral reef fishery and the oversimplification of the assumptions particularly with the use of mortality estimates applied equally across a broad range of species within each reef fish family.

The depletion-based models like DCAC and DB-SRA (MacCall 2009; Dick and MacCall 2011) provides an estimate of potential yield from an equation that originated from Gulland (1970) where sustainable yield is half of the virgin biomass once the natural mortality is accounted for. The unsustainable windfall effect of depletion from the stock biomass and the potential yield dictates the level of sustainable annual harvest. This method requires a catch time series, an estimate of natural mortality, and nominal information on stock depletion (change in abundance from first to the last year of the catch time series). Monte-Carlo simulation allows for determination of probability distribution around the sustainable yield value, biomass at MSY and catch at fishing mortality at MSY. Merging the Stock-Reduction-Analysis to DCAC incorporates a production function derived from a standard stock recruitment relationship (Dick and MacCall 2011). It also incorporates uncertainties in the natural mortality, stock dynamics, optimal harvest rates and stock status via the Monte-Carlo simulation. The depletion models were not chosen as they assume catch trends are directly associated with the abundance of fish. In reality, the fluctuations in coral reef catches in the Western Pacific Region were driven mostly by changes in the amount of effort over time and possibly changes in the data collection system. Moreover, a recent paper by Vert et al. (2013) shows catch is not a good predictor of stock abundance for most of the stocks. The fluctuations in abundance are not directly correlated with increases in catches. Depletion-based models were also shown to be highly sensitive to assumed distribution for the ratio of starting and current biomass (stock depletion levels) which typically results in overestimation of the sustainable harvest levels when this parameter was set at optimistic levels (Wetzel and Punt 2011).

The catch-MSY estimator (Martell and Froese 2012) utilizes a time series of removals (catch time series), an estimate of *r*, rate of population increase, and *k*, carrying capacity, and some assumptions about biomass at the start and end of the time series. The range of *r* as priors can be taken from FishBase (Froese and Pauly 2013) in the form of resilience. The Schaefer production model then creates annual biomass projections from a set of r and k combination that would not result in biomass that would exceed the carrying capacity or the stock being depleted. The assumption behind the biomass can be informed by augmenting the model with an independent source of biomass information. To maximize the potential and reliability of the model, fishery independent information from underwater visual census surveys using stationary point counts (SPCs) by the NOAA Coral Reef Ecosystem Division (CRED) was incorporated in the model to enhance the biomass projection. The augmented catch-MSY model will be the basis for moving the current Tier 5 reef fish stock to Tier 3; i.e., stocks that has a model-based estimate of MSY.

The goal of this chapter is to provide an overview of the modified catch-MSY approach to estimate a reference point for the coral reef fish stocks to improve specification of acceptable biological catches in the Western Pacific Region. This is the first attempt to generate MSY estimates for the reef fish stocks which is the starting point of the annual catch limit based management framework.

MODEL-BASED APPROACH TO ESTIMATING MSY

DATA PREPARATION: MANAGEMENT UNIT SPECIES GROUPING

In the initial ACL specification, the different management unit species are grouped into family levels and ACLs were specified only to the families that comprise 90% of the total catch. This was done to reduce the number of groups that would require ACLs as well as these groups are the ones harvested in large amounts in the fishery. The rest of the families were grouped as the bottom 10% of the catch and was assumed not to be significant in terms of total landings.

The data used in the initial ACL specification was up to 2008 for the territories and 2009. In the re-analysis of the data to be used in the model based approach, the data was updated to 2012 and the catch data for the Territories was from the creel surveys (proxy for total catch to include shore-based and boat-based catch with varying levels of non-commercial catches from multiple gear) and dealer reports (commercial catch). Each data set captures different facets of the coral reef fishery. For example, the night-time spearfishing is almost entirely missed by the creel survey since the surveys are conducted during daytime while the fishery operated at night. The night time spear fishery is better captured in the dealer reports. The Hawaii data was only for commercial based on the catch reports filed by fishermen with CMLs. No non-commercial catch were accounted for. In the process of identifying the top 90%, the results yield a different grouping compared to the initial specification. This has legal ramifications because the National Standard 1 required stocks subject to ACL specification be identified. This has to be a static list that will be easy to monitor over time. Process-wise this will result in the re-calculation of the top 90% every time new data is available otherwise it is not utilizing best scientific information available. Shifting species groups that require ACLs is hard to monitor and will result inconsistencies in the specification that ultimately will confuse the stakeholders. The current species groupings are the groups being monitored by the Archipelagic Plan Team and described in the Council annual reports. By using these fixed groupings, it will enable consistent monitoring of catches and groups that would require ACLs should new data become available.

DATA PREPARATION: CATCH TIME SERIES

Catch time series were generated from the boat-based and shore-based creel surveys conducted in American Samoa, Guam, and CNMI. The creel survey program generates an expanded catch from the participation counts that generate effort estimates and catch per unit effort from the catch intercept interview phase. The expanded catch covers only areas that are surveyed, and adjustment factors (when available and updated) are used to estimate total catches (limited). The catch data is summarized to family level. The data summaries were provided by the Western Pacific Fishery Information Network (WPacFIN), which is a program of the National Marine Fisheries Service (NMFS) – Pacific Island Fisheries Science Center (PIFSC).

In addition, the commercial catch data for the island jurisdictions (American Samoa, Guam and CNMI) (Figure 1) were extracted from the WPacFIN website (http://www.pifsc.noaa.gov/wpacfin). These data were generated from the commercial receipt book. The commercial landings from the website were summarized to family level in order to be compatible with the creel survey summaries. The commercial and creel survey catches were then summed to generate a more holistic total catch estimate. As mentioned earlier, some fisheries are better captured in one data collection system than the other. It is noteworthy, however, to realize that dealer reports and creel survey estimates are likely to be underestimating the true-total catches hence the issue of double counting may not be of significant importance.

The Hawaii catch time series was generated from the state's Division of Aquatic Resources commercial catch reporting system, which include monthly catch reports from Commercial Marine License holders and vendors. This time series was summarized by coral reef fish families. Unfortunately, the re-estimated recreational catch information (S. Pooley, Pacific Island Fisheries Science Center, pers comm) was incomplete and could not be incorporated here. This would have improved the catch time series to facilitate the evaluation of the non-commercial aspect of the fishery. The re-estimation effort will be conducted for all US Western Pacific State and Territories, but this chapter will only focus on the preliminary results from American Samoa.

DATA PREPARATION: BIOMASS INFORMATION

Standing biomass estimates were generated from the NOAA Coral Reef Ecosystem Division (NOAA-CRED) – Rapid Assessment and Monitoring Program using Stationary Point Count (SPC) data (CRED-PIFSC 2013). Biomass estimates were summarized to family level. Biomass estimates were derived from two to four SPC surveys from approximately 1,294 random sites in American Samoa, Mariana Islands, and the Main Hawaiian Island. The mean biomass was then expanded to hard bottom areas 0-30m of different habitat type (treated as strata) from the mapping division of NOAA-CRED (Williams 2010) (Figure 3). This generated a standing stock biomass at the family level for each island in the Western Pacific Region. These data included only species that occur in the fishery and were more than 15cm in total length (typical minimum fish size in the catch). There were three years of biomass estimates for American Samoa, two for Mariana Island Archipelago and one year for Hawaii. The dispersion of points around the mean biomass value per strata also known as coefficient of variation (CV) was estimated for each of the reef fish family for the most recent year of the survey and was weighted by sample size to determine CVs for other years.

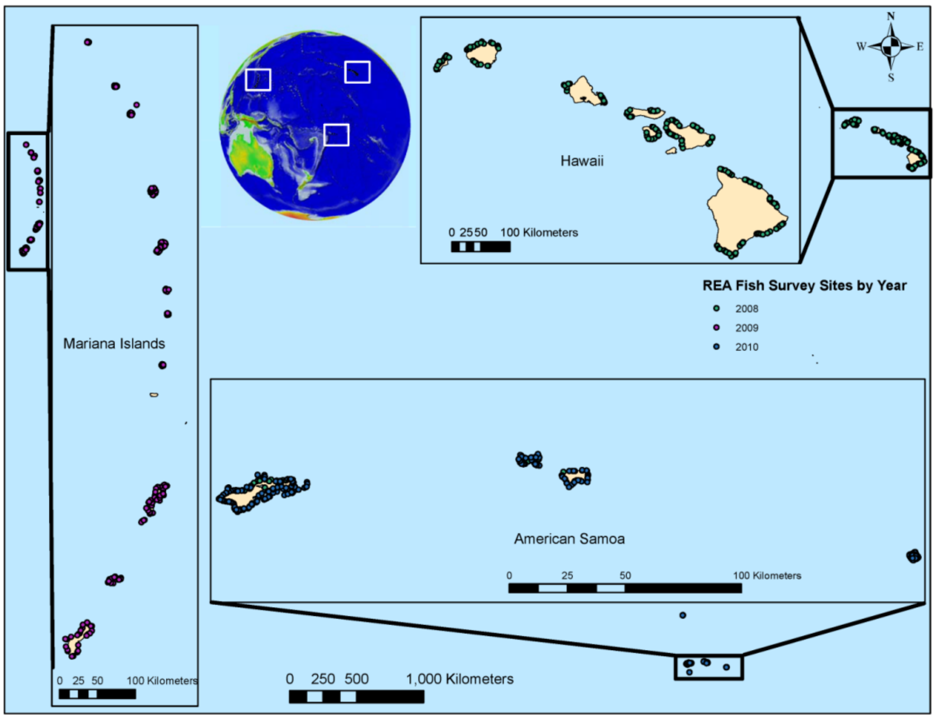

Figure 3. Map of the randomly selected sampling locations of NOAA-CRED Rapid Assessment and Monitoring Program that generated the standing biomass estimates from 2008 to 2010. The sampling sites shown are only for biomass data used in the analysis. Biomass data exist for the Northwestern Hawaiian Islands and Pacific Remote Island Areas. Map was provided by Kaylyn McCoy of NOAA-CRED.

AUGMENTED CATCH-MSY METHOD

MSY estimates were based on a modification of a method for estimating MSY that relies only on a time series of catch, assumptions about the approximate level of resilience of the stock, and the assumed ranges of depletion at the start and end of the time series (Martell and Froese, 2012). It is assumed that the stock follows Schaefer model dynamics with parameters r and k from which MSY is given by:

Eq1: $\text{MSY} = rk/4$

where r is the maximum population growth rate and k the carrying capacity. Carrying capacity is the maximum equilibrium population biomass to which the population will approach in the absence of interference (Gulland 1985). The maximum population growth rate is how fast the population grows to attain carrying capacity as affected by the environment and biological factors combined. The rate of population growth would vary depending on where the abundance is relative to carrying capacity. A positive population growth rate is expected when the population is below carrying capacity and the reverse is true is above carrying capacity. The population is controlled by a range of regulating factors such as space, food availability, predation rate by other population etc.

The difference equation form of the Schaefer model is

Eq2: $$b_{t+1} = \left[b_t + rb_t\left(1 - \frac{b_t}{k}\right) - c_t\right]\exp(\epsilon_t)$$

where b_t is biomass at time *t*, c_t is catch at time *t*, and where the exponential term (the process error) allows for inaccuracies in the model predictions. . The error, ε_t, is given by random draws from the normal distribution, $N(0, \sigma)$, where σ is an assumed measure of confidence in the applicability of the Schaefer model. The catch-MSY fits the Schaefer model to the known catch data by searching for combinations of *r*, *k*, that produce plausible outcomes; that is, the Schaefer model output must pass a series of tests which are detailed below. The procedure is summarized in the flow chart in Figure 3.

On entry (Step 1 in the chart), a time series of annual observed catch is read along with observed biomass and its coefficient of variation (CV) at whatever years biomass was measured if any. Then a text item is read indicating "resilience" which describes stock productivity and resistance to fishing pressure. Resilience determines range of *r*-values to search (Table 1). Resilience descriptors are available for all stocks on FishBase (Froese and Pauly, 2013). The next item, or items, in Step 1 provide optional overrides for ranges, including the *r*-range given by resilience and other ranges described below. The parameter *k* is generally more of an unknown than *r*, so its default is a very broad range from maximum observed annual catch up to a large value with default of 100 times the maximum annual catch. The multiplier of 100 for the upper end of the *k* range can be overridden in Step 1 by input of a different multiplier. The process error, σ, can also be input in Step 1; it is zero by default. Finally the default value of 1.0 for the CV multiplier, which is used in Step 9, can be overridden by input of ρ in Step 1.

Table 1. Default range of rate of population increase for each “resilience” level from FishBase.

Resilience	Range of *r* ($year^{-1}$)
"very low"	0.015 – 0.1
"low"	0.05 – 0.5
"medium"	0.2 – 1.0
"high"	0.6 – 1.5

Step 2 in the flow chart deals with the variable λ defined as the ratio of biomass to carrying capacity. λ_0 is that ratio at time zero, and λ_n is that ratio at time *n* where *n* is the last year in the catch time series. Step 2 determines an appropriate range for λ_0 and defines a vector of λ values spread over that range. By default the range depends on the whether the catch at the start of the time series is greater or lesser than half the maximum catch as in Table 2. The theory is that if the catch is small at the start then it is likely that the population would have experienced minimal depletion from the fishery and the biomass would be close to the carrying capacity. On the other hand, a large catch at the start would imply the population would have been somewhat depleted at the start. Note that the theory depends on the assumption that the fishery is having a significant effect on the population at least at some time during the life of the fishery. The default λ_0 range can be overridden by a range entry in Step 1 of the flow chart. Once the range is determined, a vector of λ_0 values spread over that range is defined for later use in setting b_0 from the formula $b_0 = \lambda_0/k$. A range of values is also determined by default for λ_n in a similar way to λ_0 (Table 3), with similar justification. This range can likewise be overridden by an entry in Step 1. It is used in testing *r*, *k* pairs (Step 11).

Table 2. Default range for ($\lambda_0 = b_0/k$).

(catch at time 1)/max(catch)	λ_0 range
<0.5	{0.5 – 0.9}
>0.5	{0.3 – 0.6}

Table 3. Default range for ($\lambda_n = b_n/k$).

(catch at time *n*)/max(catch)	λ_n range
<0.5	{0.01 – 0.4}
>0.5	{0.3 – 0.7}

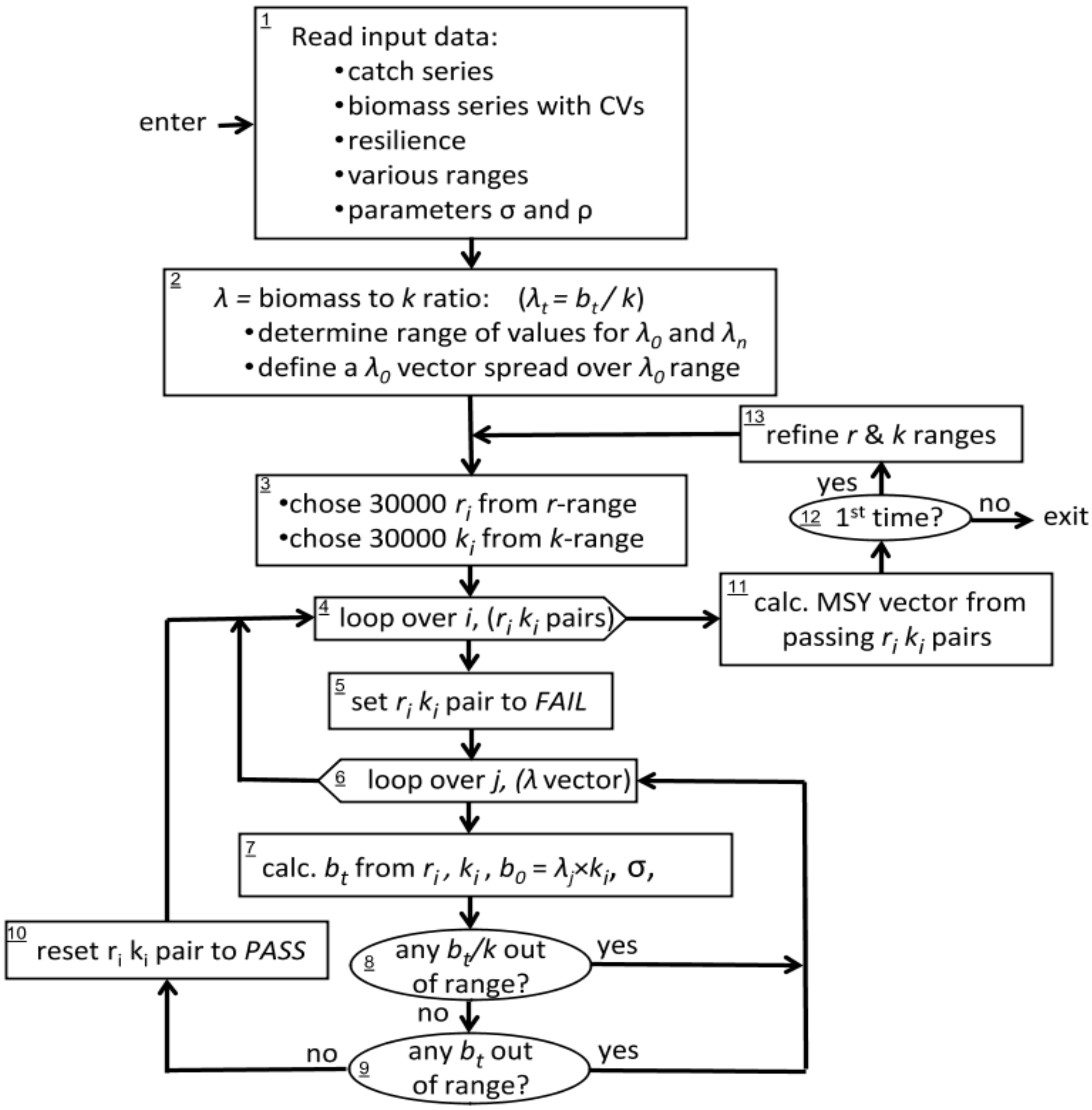

Figure 4: Flow diagram describing the model structure of the biomass augmented catch-MSY approach.

In Step 3 a large number (30,000 by default) of values for r and k are sampled from uniform distributions over the respective ranges. The graphical illustration of the *r*-*k* pairing is shown in Figure 4. Step 4 runs a loop (indexed by *i*) testing each r_i, k_i pairs for plausibility. The first step in the loop (Step 5) sets a test flag to FAIL for the r, k pair after which Step 6 runs another loop over elements of the λ vector indexed by *j* and defined in Step 2.

Step 7 implements the Schaefer model (Equation 2) based on the current *r*, *k* pair and on b_0 calculated from the current *k*, as well as σ if it is non-zero. The output of the Schaefer model is a time trajectory of biomass values, b_t starting from $t=0$.

Following Step 7 the b_t/k ratio is first tested for all time steps. This includes testing whether in the final step the ratio b_n/k is outside the λ_n range, and for all other time steps, whether the ratio is outside the range 0 to1 (i.e. biomass less than zero or greater than *k*). Note that this test depends on the current value of *k* which is itself unknown.

The next test (Step 9) constitutes the augmented part of the catch-MSY technique. It is more stringent than the test in Step 8 in that the absolute value of b_t is tested against measured values of biomass for those times where such measurements were made. Failure is indicated if b_t is outside an allowable biomass range determined by the measured biomass and its CV times a multiplier, ρ, which defaults to 1.0.

Failure in either test ("yes" to the question in the ellipse) leads to the top of the inner loop (Step 6), and the tests are repeated with the next element of the λ vector and therefore with a new value of b_0. If the loop governed by Step 6 is exhausted, control will pass out the pointed end of the box to the top of the outer loop at step 4 with the test flag still set to FAIL. Another *r*, *k* pair will then be tested. Otherwise, if both tests pass for any iteration of the inner loop, then control will pass to Step 10 where the test flag will be set to PASS. Controls will then break out of the inner loop and proceed to the top of the outer loop at Step 4 to test another *r*, *k* pair.

Once the outer loop is exhausted, control passes to Step 11 where MSY is calculated for all the *r*, *k* pairs with test flag set to PASS. Then if Step 12 is entered for the first time, control will pass to step 13 where refined ranges for *r* and *k* are established before proceeding back to Step 3 for a second phase of the procedure. The ranges are refined so as to focus the search in the second phase to areas of *r* and *k* space that are more likely to yield *r*, *k* pairs that pass the test.

To refine the *r* and *k* ranges, r^*, k^*, and Y^* are defined respectively as vectors of *r* and *k* values that passed the test and a vector of MSY values calculated from those *r* and *k* values, i.e. from Equation 1, $Y_i^* = r_i^* \times k_i^*/4$. The new *r* range is then set by

$$\text{new-}r\text{-range} = \{\min(r^*) \ \cdots \ 1.2 \times \max(r^*) \ \}$$

For the refined *k* range a tentative maximum, x_a, is set to the minimum of the k^* values associated with r^* values within the lowest 10% of the original *r* range during the first phase of the procedure, i.e.

$$x_a = \min[k^* \mid r^* < 1.1 \times \min(\text{first } r \text{ range })]$$

and a second tentative maximum, x_b, is set to the Y^* values that are less than the geometric mean of all the Y_m values, i.e.

$$x_b = \max\left[k^* \left| Y^*(r^*, k^*) < \exp\left(\overline{\log(Y^*)}\right)\right.\right]$$

The new *k* range is then set by

$$\text{new-}k\text{-range} = \{0.9 \times \min(k^*) \ \cdots \ \min(x_a, x_b)\}$$

GROUND-TRUTHING THE AUGMENTED CATCH-MSY APPROACH USING SIMULATED DATA

In finding the plausible combination of *r, k* pair, the model appears to assume an inverse relationship between the priors (Figure 5). Carrying capacity is the asymptotic limit in the population controlled by environmental factors as well as biological factors like density dependent predation and resource availability. The lower the carrying capacity, the faster the population reaches the asymptotic maximum assuming that the population grows exponentially. The higher the carrying capacity the slower the population can reach the asymptotic maximum. This rate of population growth rate also depends on the stock in question whether the species that comprise the stock is r-select of k-select species. This relationship is true for most of the range of coral reef species from slower growing groupers, parrotfish and wrasses to species with high turnover rates like siganids, scads, and jacks. The combinations that fall within the bounds of this inverse relationship are the ones accepted by the model to generate a distribution around the MSY estimate.

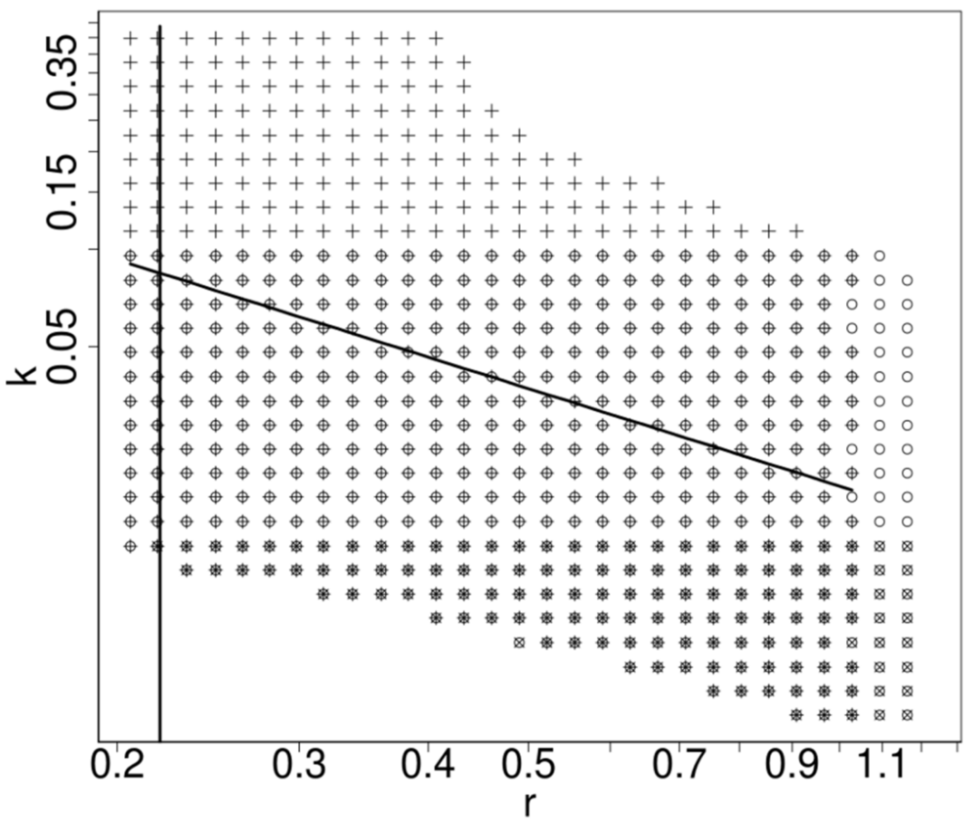

Figure 5: Example choice for upper end of *k* range. + signs indicate k^* values from first phase of testing. Vertical line indicates 1.1 times the low end of the first *r* range, and × signs indicate values chosen for x_a. Slanted line indicates locus of r^* and k^* values corresponding to the geometric mean of all the Y^* values, and O signs indicate values chosen for x_b. See text for further explanation.

A simulation study of the catch-MSY technique examined the performance and sensitivity of the technique and the effect of incorporating observed biomass data. The simulation utilized data sets with and without biomass estimates, and the simulation results were compared to a known quantity of MSY. The model was tested for sensitivity to biomass information at varying degrees of fishing mortality (Figure 6). The simulation without biomass data showed the model generating a lower MSY estimate at F=0.01 to 0.05. The model generated an MSY estimate close to the true/known MSY at F=0.10 and remained close to the true value thereafter. When biomass information is included, the MSYs generated were consistently above the true value across a wide range of F but not nearly as biased as the results with no biomass input and low F. Plots of good *r*, *k* pairs (Figure 7) show that more accurate results are obtained when the field of good *r*, *k* pairs spans true MSY, but biased results are obtained when such is not the case as in Figure 7A corresponding to the lowest red box in Figure 5.

The simulation results show that if catch is low relative to true MSY, and observed biomass data are not utilized, the method will consistently underestimate MSY.

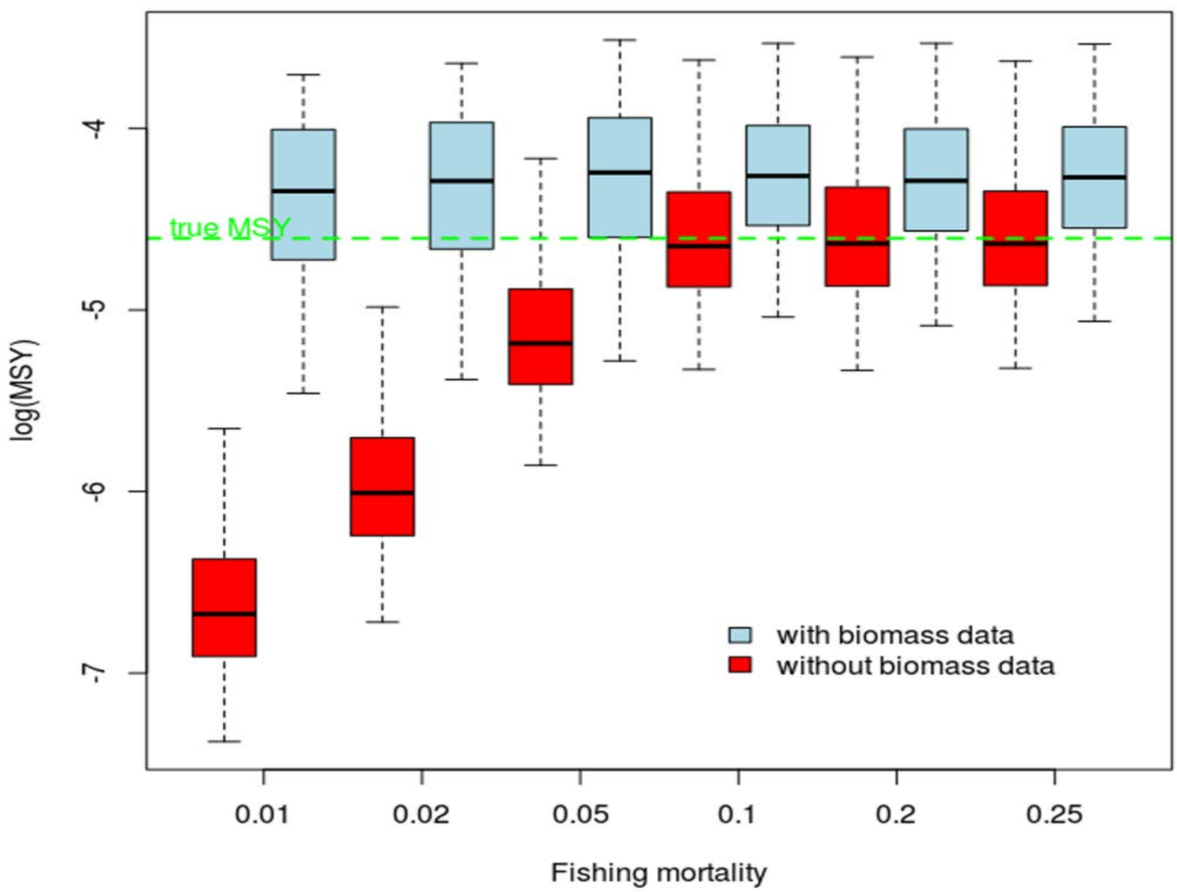

Figure 6: Paired MSY results across a broad range of fishing mortality values from model simulation using data with and without biomass information.

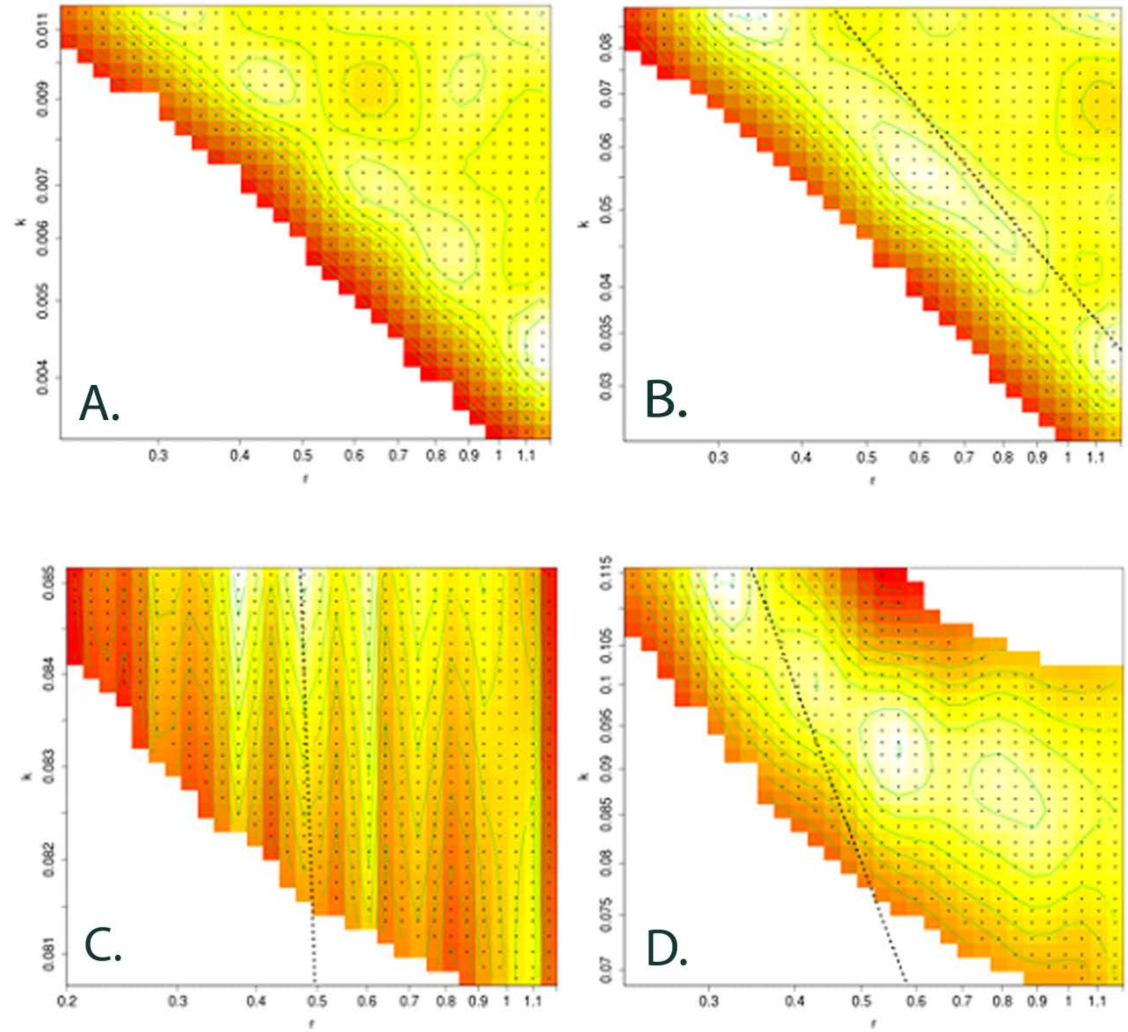

Figure 7: Pairs of good *r, k* values from second phase of 4 simulations: A) F=0.01, biomass ignored; B) F=0.10, biomass ignored; C) F=0.01, biomass included; D) F=0.10, biomass included. Dotted lines show locus of r^* and k^* values corresponding to the real MSY. In plot a. the line is off the scale to the upper right. Single dots show grid squares containing at least one good *r*, *k* pair. Contour lines and color indicate density of good *r*, *k* pairs, (white–high, red–low).

PRELIMINARY RESULTS USING REAL DATA

For the analyses presented here, the resilience for all cases was assumed to be "medium" indicating a range in r of $\{0.2 \cdots 1.0\}\text{yr}^{-1}$, depletion ranges at the start and end were set to the broad range of $\{0.01 \cdots 0.99\}$, and process error, σ, was set to 0.05.

Table 4 offers the preliminary model results for American Samoa coral reef MUS families comparing various model scenarios. The column labeled as "analysis 1" had no constraints on *r* and no biomass information. This run was not intended to represent any real estimate but to merely determine the sensitivity and effect of the *r* constraints on the estimated MSY value for model evaluation and comparative purposes. The analysis 2 and 3 had constraints applied to the priors and controlled for inclusion of biomass data (analysis 2 had no biomass data while the analysis 3 included biomass). In all cases, the MSY generated by analysis 1 generated a higher MSY estimated. Analysis 2 simulations generated lower variability in the MSY estimates (coefficient of variation – CV) and lower MSY estimates. Incorporation of biomass estimates increased the MSY in most cases with similar CVs.

Table 4. Preliminary model results for American Samoa coral reef MUS families simulating various scenarios: 1) no constraints on *r* priors; 2) priors are constrained with no independent input for biomass; 3) priors are constrained with biomass incorporated as input parameters . The numbers for MSY and bounds are expressed in 1,000 pounds.

Management Unit Species	Analysis 1: No constraints applied				Analysis 2: Constraints applied but no biomass estimates				Analysis 3: Constraints applied with biomass estimates			
	MSY	low bound	high bound	CV	MSY	low bound	high bound	CV	MSY	low bound	high bound	CV
Acanthuridae	148	89	247	0.05	49	26	89	0.08	145	80	258	0.06
Scaridae	358	246	521	0.03	27	15	49	0.09	341	233	401	0.02
Serranidae	30	16	56	0.09	14	7	25	0.12	32	16	62	0.10
Lutjanidae	172	36	830	0.15	19	10	38	0.12	54	43	79	0.04
Lethrinidae	28	7	108	0.20	17	9	31	0.11	26	14	47	0.10
Holocentridae	10	5	20	0.16	6	3	12	0.17	13	5	21	0.17
Carangidae	44	5	384	0.29	13	7	24	0.12	19	11	31	0.08
Carcharhinidae	9	3	25	0.24	1	1	2	2.88	1	3	9	0.18

The MSY estimates for the model run that has no constraints in *r* were consistently higher across all families tested. The range of values generated is typically larger if the *r* was not constrained. Constraining the prior and not incorporating biomass information resulted in a lower MSY but narrower distribution range and smaller coefficient of variation. Incorporating biomass information and constraining *r* generally resulted in a higher MSY estimate on a narrow range of values and coefficient of variation. The level of enhancement from the model run would depend on the amount of biomass information available and the CV around the biomass estimate. Acanthuridae (surgeonfish), Scaridae (parrotfish), Serranidae (grouper), Lutjanidae (snappers) and Lethrinidae (emperors) are common in underwater visual census surveys in American Samoa (Page 1998; Sabater and Tofaeono 2006; Williams et al. 2011; PIFSC 2011). The differences in MSY between model runs with and without biomass values were small for squirrelfish Holocentridae (squirrelfish), Carangidae (jacks) and Carcharhinidae (sharks) because these families are either nocturnal and/or highly mobile and are not readily captured using SPCs (Williams 2010).

IMPLICATIONS OF THE AUGMENTED CATCH-MSY APPROACH TO FISHERY MANAGEMENT IN CORAL-ASSOCIATED FISHERIES

The augmented catch-MSY approach generates an estimate of MSY for the different coral reef fish stocks that can be used as a proxy for the overfishing limit under the annual catch limit based management. This elevates the coral reef fish stocks from the catch-only tier to a model-based tier utilizing the simple Schaefer production model and an independent estimate of biomass from fishery independent surveys. In order to quantify the scientific uncertainty and determine the acceptable biological catch levels, the control rules (Figure 8) require the Council to conduct a risk of overfishing analysis (denoted by P*, henceforth will be called P* Analysis) (WPRFMC 2011). The P* Analysis is a score-based system to semi-quantitatively account for sources of scientific uncertainty based on four dimensions: 1) assessment information; 2) uncertainty characterization; 3) stock status; and 4) productivity-susceptibility of the stock. The total uncertainty score will be deducted from the 50% risk of overfishing which is equivalent to the proxy overfishing limit or the MSY estimate from augmented catch-MSY approach.

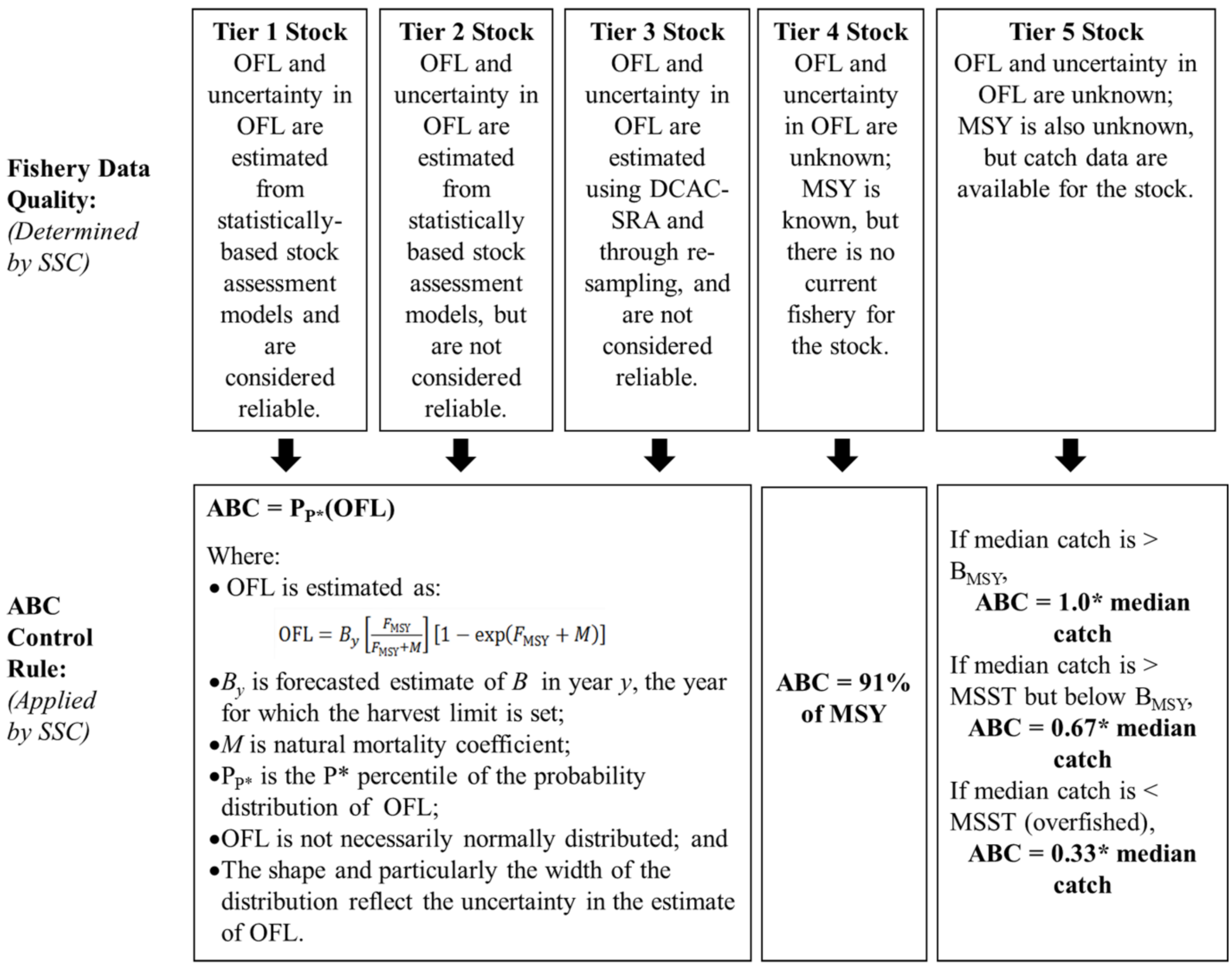

Figure 8. The Tier-System Approach of the Western Pacific Regional Fishery Management Council to determine the Acceptable Biological Catch.

The augmented catch-MSY approach generates a probability distribution around the mean MSY estimate. This can be used to generate a risk of overfishing (P*) table using quantiles of that one-tail distribution at 5% increment. The catch associated with each level of risk is the acceptable biological catch. Preliminary results of the 2013 P* analysis indicate that the total uncertainty score ranges from 23.3 to 23.6 generating a range of P* value of 26.7% to 26.3% (M Sabater, Western Pacific Regional Fishery Management Council, unpubl data). Table 5 compares the MSY estimates generated by the model, the acceptable biological catch associated with the P* of 26.3, the 2012 acceptable biological catch based on 75th percentile and the 2012 coral reef fish catches for American Samoa. The new acceptable biological catch estimates from the model based approach is generally higher than the estimates using the catch-only approach based on creel survey data. The new acceptable biological catch estimate for Family Mugilidae (mullets) is lower than the 2012 acceptable catch levels due to lack of biomass information to feed into the model. Mullets are not captured in the underwater visual census surveys since these are mostly found on reef flat and sandy bottom areas where surveys are not conducted. Striving for a better estimate of biomass as well as complete catch information improves the MSY estimation. The current Tier 5 control rule does not utilize any biomass and generic life history information which are currently available. This is the first region-wide attempt to estimate MSY for a broad range of coral reef stocks using a simple modeling approach.

The recent catches in American Samoa are small relative to the existing annual catch limits (Table 5). In this particular case, the current acceptable biological catch appears to be adequate to limit the fisheries from over-exploitation. However, not knowing what the sustainable harvest limit is from a more scientifically robust method it deprives the fishing community to explore developing its fishery. Based on the preliminary results it appears that there is still sufficient buffer for the fishery to develop. The coral reef fishery in the Western Pacific region is a low-value commercial fishery compared to the pelagic and the bottomfish fishery (Gillet 2009). The current value of the coral reef fishery based on data from 2011 was estimated to be about $111,416 (WPacFIN, Pacific Island Fisheries Science Center, unpubl data). Fishing effort in American Samoa has declined over the past decades brought about by changes in the socio-economic conditions in this US Territory (Sabater and Carroll 2009). Reliance on fishing, although still has cultural significance (Kilarski et al. 2006), had declined due to limited market as well as change in the diet and higher economic status allowing American Samoans to purchase food instead of fishing for their protein source (Ponwith, 1991; Craig et al., 1993; Saucerman, 1995a, 1995b; Coutures, 2003). Despite the low economic value, the cultural and aesthetic importance of coral reef and associated fishery resources is invaluable to the indigenous people of the Western Pacific.

Table 5. Comparison of recent catches, established annual catch limits and estimated MSYs using the modified catch-MSY model in American Samoa. Values are expressed in pounds.

Family	MSY estimate	New ABCs	2012 ABCs	2012 catch
Acanthuridae-surgeonfish	145,500	116,000	19,516	6,394
Lutjanidae-snappers	54,000	46,000	18,839	2,240
Carangidae-jacks	18,400	15,400	9,460	2,374
Lethrinidae-emperors	25,700	20,400	7,350	1,889
Scaridae-parrotfish	341,300	299,000	8,145	2,807
Serranidae-groupers	31,500	24,500	5,600	1,325
Holocentridae-squirrelfish	13,700	11,900	2,585	905
Mugilidae-mullets	3,100	2,500	2,857	1,252

A significant potential for maximizing the economic yield in the coral reef fishery has yet to be tapped. The information provided in Table 5, which is a subset of the coral reef fishery, can be translated to economic values. For this set of reef fish families, the 2012 catches can be valued at approximately $53,721 at an average of $2.80 per pound of reef fish. If the catches were to be maximized close to or at annual catch limit (or the acceptable biological catch because both were set equal to each other) levels, then the potential economic value is estimated to be at $208,186, quadruple the value of what was caught in 2012. If the fishery operated close to the estimated new acceptable biological catches, the potential economic gain is estimated at $1,499,960. This is eight-times more than what is allowed under the current annual catch limits and a 31-fold increase in 2012 landings. Although the potential for maximizing the economic yield is there, the coral reef fishery in the Western Pacific region is small and diverse and would require significant increase in fishery participants and investment upgrade the current fishery operation. Due to the low fishery participation, local markets augment the fish demand by importing reef fish from the neighboring island nations (Sabater and Carroll 2009). The current level of fishing in the small island US Territories and Commonwealth may already be at its optimum. The importance of coral reef fishery is not only for commercial but for traditional and cultural purposes as well (Levine and Allen 2009, Allen and Amesbury 2012). The coral reef fishery started out as means to feed the community and has communal importance. This is still practiced in the Western Pacific region through barter, trade and customary exchange (Severance et al. 2013). The cultural and traditional importance of this fishery cannot be translated to any economic value but is deemed important to maintain cultural identity and relationships between communities.

Managing the fishery to attain optimum yield is one of the goals of the Magnuson-Stevens Fishery Conservation and Management Act. However on a national level, managing the fishery to attain optimum yield is overshadowed by the need to addressing overfishing. The model-based approach allows for estimation of a reference point for the overfishing limit based on more than just catch data. Optimum yield may have already been achieved for the Western Pacific coral reef fisheries since it would entail significant investment in developing the fisheries to maximize the potential economic yield. Given the current modest commercial value of the coral reef fishery, a simple assessment method such as the augmented catch-MSY approach provides a practical way to provide scientific advice to manage the fishery compared to the amount to be spent on conducting a formal stock assessment for large high value commercial fishery.

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APPENDIX 1.

Estimates of Maximum Sustainable Yield (expressed in thousands of pounds) from the Augmented Catch-MSY Approach in American Samoa, Guam, CNMI and Hawaii. Resilience information was from FishBase. Each reef fish families were assigned a specific resilience based on the all species that comprise the reef fish family in the catch. If there is a mix of resilience information within the family, the resilience used was for the species that dominate the catch under each respective family. Also presented is the standard deviation in the normal distribution, mode of the MSY values, and the confidence intervals. The biomass column indicates the number of years with biomass information (0 indicates no biomass information)

Results are given for two separate methods for revising the range of k values for the second round of choosing and testing r-k pairs. Method A is the method most likely to be chosen by the original version of catch-MSY. The choice doesn't affect the outcome very much with input of biomass data, but there is a significant difference without biomass data.

Hawaii

group	biomass samples	k-revise A MSY (mean.log)	sigma	mode	5%	95%	No.	k-revise B MSY (mean.log)	sigma	mode	5%	95%
S. crumenopthalmus	0	986.0	0.15	969.4	791.8	1290.7	1	1150.8	0.2	1137.7	806.7	1713.1
D. macarellus	0	416.0	0.16	406.5	335.6	557.4	2	538.0	0.3	531.2	345.5	889.5
Acanthuridae	1	296.0	0.43	295.5	145.0	601.9	3	445.5	0.5	452.6	195.6	953.6
Carangidae	1	173.3	0.30	170.1	111.8	287.9	4	185.1	0.3	183.7	114.1	312.7
Charcarhinidae	1	11.2	0.21	11.7	7.6	14.2	5	12.4	0.6	12.5	4.3	34.7
Holocentridae	1	143.5	0.11	138.9	128.0	181.9	6	159.8	0.1	158.1	137.8	193.0
Kyphosidae	1	88.4	0.18	83.6	72.9	124.8	7	122.8	0.3	119.6	86.0	195.5
Labridae	1	175.1	0.12	170.3	152.9	237.6	8	229.2	0.2	227.4	174.6	317.1
Lethrinidae	1	30.7	0.14	29.7	26.0	40.8	9	39.6	0.2	39.4	29.4	54.8
Lutjanidae	1	278.0	0.17	265.5	229.9	385.4	10	359.3	0.2	356.2	264.4	506.5
Mollusk	0	41.5	0.33	39.6	26.0	75.3	11	50.3	0.4	49.5	26.6	99.8
Mugilidae	0	22.0	0.26	21.5	14.8	34.5	12	24.6	0.3	24.5	14.3	43.0
Mullidae	1	161.0	0.29	159.5	101.3	264.1	13	195.7	0.3	197.5	116.4	324.3
Scaridae	1	214.0	0.18	212.2	170.9	297.5	14	271.5	0.2	270.6	200.7	373.2
Serranidae	1	106.2	0.22	100.7	81.6	154.9	15	141.3	0.2	139.9	98.7	212.3
Other CREMUS	1	431.7	0.15	419.5	361.2	601.6	16	540.8	0.2	535.6	404.5	747.2
Spiny lobster	0	152.4	0.17	152.3	114.8	202.6	17	204.6	0.4	192.0	116.8	415.7
CRE-crustaceans	0	37.8	0.27	38.0	23.8	58.5	18	43.1	0.4	42.8	23.9	77.8

Guam

		k-revise A						k-revise B				
group	biomass samples	MSY (mean.log)	sigma	mode	5%	95%	No.	MSY (mean.log)	sigma	mode	5%	95%
S. crumenopthalmus	0	63.8	0.11	63.4	54.1	77.3	1	70.7	0.2	69.2	54.9	97.3
Acanthuridae	2	99.2	0.37	101.8	52.1	172.1	2	80.9	0.5	81.1	38.1	167.2
algae	0	10.1	0.09	10.0	8.7	11.8	3	10.5	0.2	10.0	8.4	15.4
Carangidae	1	32.0	0.11	32.4	26.2	37.2	4	30.6	0.1	31.0	24.1	37.0
Charcarhinidae	1	2.5	0.42	2.8	1.0	4.0	5	2.9	0.7	2.9	1.0	8.9
Holocentridae	2	11.5	0.22	11.6	8.0	16.7	6	12.1	0.2	11.9	8.4	17.9
Kyphosidae	1	10.1	0.15	10.1	7.8	12.9	7	9.7	0.2	9.7	7.5	12.8
Labridae	2	23.5	0.25	22.7	16.9	37.6	8	33.3	0.3	32.9	20.4	61.2
Lethrinidae	0*	49.1	0.34	47.1	29.9	90.6	9	78.0	0.6	76.6	31.5	208.6
Lutjanidae	2	27.3	0.35	26.9	15.9	49.3	10	23.9	0.3	22.5	15.0	44.9
Mollusk	0	29.2	0.34	28.8	17.0	52.7	11	49.5	0.6	47.4	18.7	150.8
Mugilidae	0	16.8	0.27	16.7	10.8	26.4	12	26.2	0.6	24.5	11.0	74.8
Mullidae	2	14.6	0.25	15.0	9.4	20.9	13	12.8	0.4	12.9	6.5	25.0
Scaridae	2	80.1	0.30	78.7	50.7	134.4	14	87.1	0.3	86.5	51.1	151.8
Serranidae	2	31.6	0.37	31.8	17.4	56.3	15	28.6	0.4	27.4	16.4	54.5
Siganidae	2	19.7	0.04	19.7	18.5	21.3	16	19.7	0.1	19.7	18.3	21.1
Other CREMUS	2	225.2	0.21	225.6	160.0	315.5	17	211.3	0.2	209.2	149.8	306.0
Spiny lobster	0	2.5	0.26	2.5	1.7	4.0	18	4.6	0.7	4.3	1.7	14.9
CRE-crustaceans	0	8.7	0.27	8.6	5.6	13.9	19	14.0	0.6	13.3	5.8	39.7

* For leth there appears to be a strong clash between the catch series and the biomass measures. The program would fail unless input of biomass was turned off.

CNMI

group	biomass samples	k-revise A MSY (mean.log)	sigma	mode	5%	95%	No.	k-revise B MSY (mean.log)	sigma	mode	5%	95%
S. crumenopthalmus	0	34.9	0.13	34.7	28.2	44.1	1	122.5	0.9	119.6	32.8	512.4
Acanthuridae	2	283.2	0.46	303.5	121.1	545.9	2	361.2	0.5	370.0	157.8	747.9
Carangidae	2	73.5	0.37	79.6	35.1	115.3	3	55.3	0.4	53.0	28.7	117.1
Holocentridae	2	56.7	0.26	53.5	39.8	95.3	4	78.5	0.3	78.0	48.9	129.6
Labridae	2	54.9	0.46	60.1	22.8	99.1	5	73.5	0.5	75.5	29.4	170.7
Lethrinidae	2	59.2	0.29	61.6	35.0	90.5	6	69.7	0.5	72.2	29.7	149.5
Lutjanidae	2	206.4	0.46	220.8	93.7	392.3	7	225.8	0.4	228.7	106.7	458.5
Mollusk	0	4.5	0.32	4.7	2.5	7.0	8	16.7	1.1	16.3	3.0	100.1
Mugilidae	0	2.2	0.31	2.2	1.2	3.5	9	7.7	1.1	7.5	1.5	45.2
Mullidae	2	31.5	0.17	31.4	23.8	40.4	10	31	0.17	30.5	24.4	41.7
Siganidae	2	10	0.21	10.3	7.6	17.1	11	12	0.32	11	7.8	19.5
Kyphosidae	2	23.5	0.46	25.2	10.2	42.1	12	29.4	0.5	30.5	12.9	60.7
Other CREMUS	2	4.3	0.3	4.4	2.5	6.7	13	14.5	1.06	14.2	2.8	83.8
Scaridae	2	145.7	0.42	157.9	62.8	252.3	14	189.9	0.5	199.0	73.5	433.2
Serranidae	2	95.7	0.47	99.2	42.5	190.9	15	110.3	0.4	112.0	51.8	222.9
CRE-crustaceans	0	2.5	0.31	2.6	1.4	3.9	16	9.1	1.1	8.9	1.6	55.4

American Samoa

		k-revise A						k-revise B				
group	biomass samples	MSY (mean.log)	sigma	mode	5%	95%	No.	MSY (mean.log)	sigma	mode	5%	95%
S. crumenopthalmus	0	34.1	0.09	33.9	30.1	39.3	1	45.3	0.3	41.1	31.8	93.6
Acanthuridae	3	145.5	0.30	140.2	94.5	257.5	2	148.6	0.3	142.5	102.7	242.0
Carangidae	3	18.4	0.26	18.8	12.3	29.3	3	24.3	0.4	23.2	14.0	41.8
Charcarhinidae	3	1.0	0.55	1.2	0.3	1.9	4	2.3	0.9	2.4	0.6	9.6
Holocentridae	3	13.7	0.18	13.3	11.1	19.5	5	16.8	0.2	16.6	12.6	23.2
Lethrinidae	3	25.7	0.31	25.5	15.8	43.1	6	23.7	0.3	23.0	14.6	42.6
Lutjanidae	3	54.0	0.18	58.6	40.0	65.7	7	65.4	0.1	66.9	46.8	78.8
Mollusk	0	15.0	0.28	15.5	9.2	23.0	8	29.6	0.7	27.5	10.0	100.1
Mugilidae	0	3.1	0.31	3.2	1.9	5.1	9	8.2	0.9	7.6	2.3	34.4
Scaridae	3	341.3	0.18	351.6	242.6	438.4	10	294.6	0.1	300.3	231.6	359.6
Serranidae	3	31.5	0.35	31.1	18.1	55.5	11	30.5	0.3	29.5	19.6	52.6
Mullidae		11.5	0.1	11.3	10	13.7	12	12.7	0.13	12.5	10.7	16.3
Siganidae		0.2	0.16	0.2	0.2	0.3	13	0.2	0.22	0.2	0.2	0.3
Kyphosidae		1.6	0.33	1.6	0.9	2.8	14	2.6	0.44	2.6	1.2	5.4
Labridae		17.5	0.28	16.7	11.7	27.2	15	19	0.25	18.1	13.4	29.2
Other CREMUS	3	16	0.31	16	9.3	26.7	16	28.5	0.68	27	10.2	91.2
Spiny lobster	0	3.8	0.32	3.7	2.3	6.6	17	7.3	0.7	7.1	2.5	24.4
CRE-crustaceans	0	3.7	0.36	3.8	2.0	6.5	18	7.8	0.8	7.3	2.3	31.3

APPENDIX 2.

Risk of overfishing tables where the 50% risk of overfishing corresponds to the estimated MSY generated by the Augmented Catch-MSY Approach. The risks are in 5% increments. The catch associated with each risk of overfishing are expressed in thousands of pounds.

Separate risk tables are given for the two methods used to revise the range of k values. The choice doesn't affect the outcome very much with input of biomass data, but there is a significant difference without biomass data.

Hawaii

A.	**k-revise A**									
group	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**
S. crumenopthalmus	791.8	819.60	843.1	861.9	879.2	896.0	913.4	931.0	949.7	969.4
D. macarellus	335.6	343.90	351.3	358.4	365.5	372.8	380.3	388.4	397.3	406.5
Acanthuridae	145.0	160.90	175.6	214.9	228.4	238.9	252.8	262.9	274.6	295.5
Carangidaegidae	111.8	118.40	124.7	130.4	136.3	142.2	148.7	155.4	162.5	170.1
Charcarhinidae	7.6	8.60	9.3	9.8	10.2	10.6	10.9	11.2	11.4	11.7
Holocentridae	128.0	129.00	130.3	131.1	131.7	133.2	134.6	135.9	137.1	138.9
Kyphosidae	72.9	73.70	74.6	75.5	77.0	78.4	79.4	80.5	81.6	83.6
Labridae	152.9	155.10	157.6	160.1	161.7	162.9	163.9	165.8	168.1	170.3
Lethrinidae	26.0	26.60	27.0	27.3	27.6	28.1	28.5	28.7	29.2	29.7
Lutjanidae	229.9	232.80	235.8	238.7	244.9	248.8	252.7	257.6	261.9	265.5
Mollusk	26.0	27.80	29.1	30.4	31.7	33.0	34.5	36.1	37.8	39.6
Mugilidae	14.8	15.90	16.8	17.5	18.2	18.8	19.3	20.0	20.7	21.5
Mullidae	101.3	111.80	117.8	123.1	129.4	135.4	140.9	146.6	152.9	159.5
Scaridae	170.9	174.10	177.1	179.7	180.8	186.2	190.5	198.4	203.5	212.2
Serranidae	81.6	82.60	85.3	87.5	89.1	90.8	92.8	95.2	97.7	100.7
Other CREMUS	361.2	366.70	372.4	378.2	385.2	391.7	398.1	403.4	409.4	419.5
Spiny lobster	114.8	122.50	127.8	131.7	135.3	139.0	142.4	145.9	149.0	152.3
CRE-crustaceans	23.8	26.30	28.2	29.9	31.5	32.9	34.3	35.5	36.8	38.0

B.	**k-revise B**									
group	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**
S. crumenopthalmus	807	850.6	886	919	952	988	1025	1061	1099	1138
D. macarellus	346	363.3	381	400	418	438	459.8	483.5	507.1	531.2
Acanthuridae	196	231.1	259	288	313	342	367.9	395.1	425.4	452.6
Carangidaegidae	114	123.3	131	139	146	154	161.2	168.1	175.6	183.7
Charcarhinidae	4.3	5.4	6.3	7.2	8	8.8	9.8	10.6	11.6	12.5
Holocentridae	138	140.6	144	146	148	150	152	154.3	156.3	158.1
Kyphosidae	86	90.5	94.5	98.1	101	105	108.6	112.1	115.7	119.6
Labridae	175	181.4	188	194	200	205	211	216.5	221.7	227.4
Lethrinidae	29.4	31	32.1	33.2	34.3	35.5	36.6	37.5	38.5	39.4
Lutjanidae	264	280.5	292	303	312	321	330.3	338.2	346.7	356.2
Mollusk	26.6	29.2	31.3	33.4	35.7	38.2	40.8	43.4	46.4	49.5
Mugilidae	14.3	15.9	17.1	18.2	19.2	20.1	21.1	22.2	23.3	24.5
Mullidae	116	128.3	138	148	157	165	173.1	181.5	189.4	197.5
Scaridae	201	213.4	223	232	239	246	251.7	257.6	264.2	270.6
Serranidae	98.7	106	111	116	121	125	128.4	132.2	136.1	139.9
Other CREMUS	405	424.2	440	457	471	485	496.5	510.6	523.5	535.6

Spiny lobster	117	126.8	135	143	150	158	165.4	172.7	181.8	192
CRE-crustaceans	23.9	26.6	29.1	31.4	33.5	35.4	37.1	38.9	40.9	42.8

Guam

A.	**k-revise A**									
	5%	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**
Acanthuridae	52.1	60.2	66.5	71.8	77	82.1	87	91.9	96.6	101.8
Algae	8.7	9	9.2	9.3	9.4	9.6	9.7	9.8	9.9	10
S. crumenophthalmus	54.1	55.8	57	58	59.1	60.2	61	61.8	62.6	63.4
Carangidae	26.2	27.7	28.5	29.3	29.9	30.5	31.1	31.5	32	32.4
Carcharhinidae	1	1.4	1.7	1.9	2.1	2.3	2.4	2.6	2.7	2.8
CRE-crustaceans	5.6	6.1	6.5	6.9	7.2	7.5	7.7	8	8.3	8.6
Holocentridae	8	8.7	9	9.4	9.7	10.1	10.5	10.9	11.3	11.6
Kyphosidae	7.8	8.3	8.6	8.9	9.1	9.3	9.6	9.7	9.9	10.1
Labridae	16.9	17.4	18	18.5	19.3	20	20.7	21.4	22	22.7
Lethrinidae	29.9	32.6	34.7	36.5	38	39.6	41.2	42.9	45	47.1
Spiny lobster	1.7	1.8	1.9	2	2.1	2.2	2.3	2.3	2.4	2.5
Lutjanidae	15.9	17.3	18.5	19.6	20.7	21.8	23	24.2	25.5	26.9
Mollusk	17	18.7	19.9	21.1	22.4	23.7	24.9	26.1	27.5	28.8
Mugilidae	10.8	11.8	12.7	13.4	14	14.6	15.2	15.7	16.2	16.7
Mullidae	9.4	10.5	11.3	11.9	12.5	13	13.5	14	14.5	15
Other CREMUS	160	171.7	181.3	188.3	195.6	201.5	207.8	213.7	219.1	225.6
Scaridae	50.7	54.9	60.2	64.2	66.1	68.1	71.6	73.9	77.4	78.7
Serranidae	17.4	19	20.5	21.9	23.4	24.9	26.5	28.1	29.9	31.8
Siganidae	18.5	18.8	18.9	19.1	19.2	19.3	19.4	19.5	19.6	19.7

B.	**k-revise B**									
	5%	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**
Acanthuridae	38.1	43.8	49	53.6	57.9	62.4	67.1	71.8	76.1	81.1
Algae	8.4	8.6	8.8	9	9.1	9.3	9.5	9.6	9.8	10
S. crumenophthalmus	54.9	57.2	59	60.6	62	63.3	64.6	66	67.6	69.2
Carangidae	24.1	25.2	26.2	27	27.8	28.5	29.2	29.9	30.4	31
Carcharhinidae	1	1.2	1.4	1.6	1.8	2	2.2	2.4	2.6	2.9
CRE-crustaceans	5.8	6.6	7.4	8.1	8.8	9.5	10.3	11.2	12.2	13.3
Holocentridae	8.4	8.9	9.4	9.8	10.1	10.5	10.8	11.2	11.6	11.9
Kyphosidae	7.5	7.9	8.2	8.5	8.7	8.9	9.1	9.3	9.5	9.7
Labridae	20.4	22.3	23.8	25.2	26.6	27.9	29.1	30.3	31.6	32.9
Lethrinidae	31.5	36.2	39.8	43.7	48	53	58	63.4	69.9	76.6
Spiny lobster	1.7	2	2.2	2.5	2.7	3	3.3	3.6	4	4.3
Lutjanidae	15	16	16.9	17.6	18.4	19.2	20	20.8	21.6	22.5
Mollusk	18.7	21.6	24.5	27.2	29.8	32.8	35.8	39.4	43.1	47.4
Mugilidae	11	12.7	14.1	15.4	16.6	17.9	19.4	20.8	22.6	24.5
Mullidae	6.5	7.4	8.2	9	9.6	10.3	10.9	11.6	12.3	12.9

Other CREMUS	149.8	159	166	172.7	178.8	184.7	191.3	196.5	203	209.2
Scaridae	51.1	56.2	60.6	64.6	68.1	71.6	75	78.6	82.3	86.5
Serranidae	16.4	17.9	19.1	20.3	21.4	22.5	23.7	24.8	26.1	27.4
Siganidae	18.3	18.6	18.7	18.9	19	19.1	19.2	19.5	19.6	19.7

CNMI

A.	**k-revise A**									
group	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**
S. crumenopthalmus	28.2	29.40	30.3	31.1	31.8	32.4	32.9	33.5	34.1	34.7
Acanthuridae	121.1	140.40	160.6	178.6	198.5	222.9	241.1	259.9	279.7	303.5
Carangidae	35.1	43.80	49.9	55.1	59.7	63.9	67.9	71.6	75.5	79.6
Holocentridae	39.8	41.40	42.6	44.9	46.5	48.4	49.1	50.6	52.5	53.5
Labridae	22.8	27.40	31.1	35.8	39.5	43.2	48.5	51.8	55.9	60.1
Lethrinidae	35.0	39.40	42.7	45.6	48.6	51.3	53.9	56.5	59.2	61.6
Lutjanidae	93.7	106.20	119.3	126.5	143.7	156.2	174.4	185.7	199.7	220.8
Mollusk	2.5	2.90	3.2	3.4	3.7	3.9	4.1	4.3	4.5	4.7
Mugilidae	1.2	1.40	1.5	1.7	1.8	1.9	2.0	2.1	2.2	2.2
Mullidae	23.8	25.1	25.7	26.4	27.6	28.7	29.7	30.4	30.7	31.4
Siganidae	7.6	7.9	8.1	8.3	8.4	8.6	8.8	9.7	10.1	10.3
Kyphosidae	12.2	14.2	16.1	18	20	21.6	23.2	25	26.7	28.7
Other CREMUS	2.5	2.8	3.1	3.3	3.6	3.8	3.9	4.1	4.3	4.4
Scaridae	62.8	77.70	89.6	101.3	111.3	121.7	130.7	139.5	148.4	157.9
Serranidae	42.5	48.20	54.5	60.9	67.0	72.6	78.9	86.0	92.6	99.2
CRE-crustaceans	1.4	1.60	1.8	1.9	2.0	2.2	2.3	2.4	2.5	2.6

B.	**k-revise B**									
group	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**
S. crumenopthalmus	32.8	37.8	43.6	50.4	58.2	66.9	77.4	89.4	103.3	119.6
Acanthuridae	158	184.6	211	234	258	279	302.6	324.6	347.5	370
Carangidae	28.7	32.1	34.8	37.3	39.8	42.3	44.9	47.4	50.1	53
Holocentridae	48.9	53.3	56.7	59.9	63.1	66.1	69.3	72.1	75	78
Kyphosidae	12.9	15.1	17	18.9	20.8	22.7	24.6	26.5	28.5	30.5
Labridae	29.4	35.2	40.4	45.2	50.2	55.1	59.9	65.2	70.2	75.5
Lethrinidae	29.7	34.7	39.7	44.5	49.2	53.7	58.2	62.5	67.2	72.2
Lutjanidae	107	123.4	137	150	164	177	190.4	202.7	215.1	228.7
Mollusk	3	3.9	4.8	5.8	6.9	8.2	9.8	11.6	13.7	16.3
Mugilidae	1.5	1.9	2.3	2.7	3.2	3.8	4.5	5.3	6.4	7.5
Mullidae	24.4	24.9	25.5	26.1	26.8	27.7	28.4	29.2	29.8	30.5
Siganidae	7.8	8.1	8.4	8.7	9.3	10.2	10.4	10.6	10.9	11
Kyphosidae	12.9	15.1	17	18.9	20.8	22.7	24.6	26.5	28.5	30.5
Other CREMUS	2.8	3.7	4.4	5.2	6.2	7.3	8.5	10.1	12	14.2
Scaridae	73.5	88.9	103	117	129	144	157.3	171.1	185.1	199
Serranidae	51.8	60.2	67.3	74.1	80.4	86.9	92.8	99.3	105.3	112
CRE-crustaceans	1.6	2.10	2.6	3.1	3.7	4.4	5.3	6.3	7.5	8.9

American Samoa

A.	**k-revise A**									
group	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**
S. crumenopthalmus	30.1	30.5	30.9	31.6	31.9	32.3	32.7	33.1	33.7	33.9
Acanthuridae	94.5	101.4	106	111	116	123	127	129.4	133.7	140.2
Carangidae	12.3	13	13.9	14.8	15.4	15.7	16.3	17.4	18.1	18.8
Charcarhinidae	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
Holocentridae	11.1	11.3	11.5	11.7	11.9	12.1	12.2	12.5	12.8	13.3
Lethrinidae	15.8	17.3	18.3	19.4	20.4	21.3	22.3	23.3	24.4	25.5
Lutjanidae	40	42.1	42.6	44.2	46	47.3	50.5	55.6	57.1	58.6
Mollusk	9.2	10.3	11.1	11.8	12.5	13.1	13.7	14.3	14.9	15.5
Mugilidae	1.9	2	2.2	2.4	2.5	2.7	2.8	2.9	3.1	3.2
Scaridae	243	267.3	279	288	299	311	320.8	332	340.3	351.6
Serranidae	18.1	19.7	21.3	22.7	24.5	25.7	27	28.3	29.7	31.1
Mullidae	10	10.3	10.4	10.5	10.8	10.9	11	11.2	11.3	11.3
Siganidae	0.12	0.13.	0.14	0.14	0.15	0.16	0.17	0.18	0.19	0.20
Kyphosidae	0.9	1	1.1	1.1	1.2	1.3	1.4	1.4	1.5	1.6
Labridae	11.7	11.9	12.4	13.5	14.1	14.3	15	15.5	16.2	16.7
Other CREMUS	9.3	10.5	11.4	12.2	12.9	13.6	14.2	14.8	15.4	16
Spiny lobster	2.3	2.5	2.7	2.9	3	3.2	3.3	3.4	3.6	3.7
CRE-crustaceans	2	2.3	2.4	2.6	2.8	3	3.2	3.4	3.6	3.8

B.	**k-revise B**									
group	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**	**35%**	**40%**	**45%**	**50%**
S. crumenopthalmus	31.8	32.5	33.3	34.2	35	35.6	37.4	38.4	39.6	41.1
Acanthuridae	103	108.4	113	117	122	125	129.4	133.8	138	142.5
Carangidae	14	15.8	17	18.2	19.3	19.9	20.8	21.5	22.1	23.2
Charcarhinidae	0.6	0.7	0.9	1.1	1.3	1.5	1.7	1.9	2.1	2.3
Holocentridae	12.6	13.3	13.8	14.3	14.7	15.1	15.5	15.9	16.2	16.6
Lethrinidae	14.6	15.8	16.9	17.8	18.6	19.6	20.4	21.3	22.1	23
Lutjanidae	46.8	54	58.8	60.6	62	63.1	64.4	65.3	66.1	66.9
Mollusk	10	11.9	13.6	15.2	16.8	18.4	20.2	22.4	24.7	27.5
Mugilidae	2.3	2.7	3.2	3.6	4.1	4.6	5.2	5.9	6.7	7.6
Scaridae	232	240.8	249	260	268	272	280.1	285.1	290.2	300.3
Serranidae	19.6	21.1	22.2	23.3	24.3	25.3	26.3	27.3	28.3	29.5
Mullidae	10.7	10.9	11.2	11.4	11.7	11.9	12	12.1	12.3	12.5
Siganidae	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Kyphosidae	1.2	1.4	1.6	1.7	1.9	2	2.2	2.3	2.5	2.6
Labridae	13.4	14.1	14.7	15.2	15.7	16.2	16.6	17.1	17.5	18.1
Other CREMUS	10.2	12.1	13.7	15.2	16.8	18.4	20.3	22.2	24.5	27

Spiny lobster	2.5	2.9	3.3	3.7	4.1	4.6	5.1	5.7	6.4	7.1
CRE-crustaceans	2.3	2.8	3.3	3.8	4.3	4.7	5.3	5.9	6.5	7.3