Ocean and Coastal Management 152 (2018) 100–119

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

An adaptive assessment and management toolkit for data-limited fisheries

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1. Introduction

Although small-scale fisheries are important livelihood sources for more than 200 million people worldwide (FAO, 2017), most lack formal stock assessments and comprehensive resource management (Costello et al., 2012). Conventional stock assessments involve complex, data-hungry models, but often the managers of small-scale fisheries have neither the requisite biological nor catch data to use these models, nor sufficient resources to obtain the necessary data (Carruthers et al., 2014; Honey et al., 2010). In these data-limited fisheries, managers often struggle to assess the status of fish stocks and implement science-based management. The ensuing lack of appropriate management measures can lead to ecological degradation and diminished economic and social benefits from fisheries (Beddington et al., 2007; Willman et al., 2009). Where no other options exist, some have even made the case for implementing not only precautionary management, but data-less management, which utilizes only local ecological knowledge (LEK) and information gathered from similar systems (Johannes, 1998).

To address data shortfalls, a number of tools have been developed for the assessment and management of data-limited fisheries. Fisheries managers have access to a suite of data-limited assessment methods relying on fishery-dependent and –independent data combined with information on species life history (e.g., Babcock and MacCall, 2011; Ehrhardt and Ault, 1992; Honey et al., 2010; Hordyk et al., 2014). These methods rely on varying data types and assumptions, and produce different indicators of fisheries status such as fishing mortality or spawning potential ratio (SPR). Additionally, to accompany the proliferation of data-limited assessment methods, scientists and managers have developed several tools to facilitate their use and the interpretation of their results. Examples include the Data Limited Fisheries Toolkit, an R package that provides multiple assessment methods and allows for Management Strategy Evaluation (MSE) comparisons (Carruthers, 2014; Newman et al., 2014); the NOAA Fisheries Toolbox, a compilation of biological modelling software for fisheries stock assessments that includes some data-limited methods but lacks guidance on interpreting results for management (NOAA, 2014); the Food and Agriculture Organization's Ecosystem Approach to Fisheries Toolbox, a framework that includes guidance on selections of assessment methods and a framework for stakeholder engagement (FAO Fisheries and Aquaculture Department, 2016); the Environmental Defense Fund's Framework for Integrated Stock and Habitat Evaluation (FISHE), which provides tools and a step-by-step framework (Environmental Defense Fund, 2013); the Science for Nature and People working group's tool, FishPath, a decision-support software that guides users through a process of characterizing their fishery based on ecological, socioeconomic, and governance factors and then identifies potential management strategies (Dowling et al., 2016); and the Traffic Light (TL) approach, which integrates multiple quantitative and qualitative criteria to assign management responses to fisheries (Caddy, 1999, 2015; Caddy and Mahon, 1998). While each of these frameworks provide valuable information on some aspect of the assessment or management process, none of them guide decision makers throughout the entire process from data compilation to adaptive assessment management with the help of a user-friendly dashboard.

The Adaptive Fisheries Assessment and Management (AFAM) Toolkit draws from the best available science and existing tools to guide

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https://doi.org/10.1016/j.ocecoaman.2017.11.015
Received 8 June 2017; Received in revised form 21 November 2017; Accepted 21 November 2017
0964-5691/

Abbreviations

AFAM	Adaptive Fisheries Assessment and Management
CPUE	Catch-Per-Unit-Effort
EDF	Environmental Defense Fund
FMP	Fishery Management Plan
HCR	Harvest Control Rule
KNP	Karimunjawa National Park
LBAR	Average length method for calculating fishing mortality
LEK	Local ecological knowledge
LRP	Limit Reference Point
MSE	Management Strategy Evaluation
MSY	Maximum Sustainable Yield
NTZ	No-take zone
PI	Performance Indicator
PSA	Productivity Susceptibility Analysis
SPR	Spawning Potential Ratio
TRP	Target Reference Point
TURF	Territorial Use Rights in Fisheries

managers through the process of data compilation, fishery performance assessment in data-limited contexts, results interpretation, management response implementation, and adaptive management over time through iterative feedback. AFAM is a comprehensive framework that is designed for small-scale fisheries with varying amounts of data and limited technical capacity. AFAM's unique contributions to the field of data-limited fisheries assessment and adaptive management include: 1) a user-friendly and user-useful open-source dashboard that can be used online or offline to facilitate data analysis and interpretation; 2) accompanying hyperlinked guidance documentation which contains decision-trees, reference tables, and case studies; and 3) a process for synthesizing multiple performance indicators from independent data sources using LEK, and adaptively adjusting management decisions based on new information and changing dynamics. Importantly, while the toolkit provides information on the tradeoffs and implications associated with each step, it is not prescriptive and does not provide fishery-specific advice – final management decisions are still left to the discretion of the stakeholders involved. Additionally, the toolkit is not meant to be a replacement for more traditional stock assessment and management where the data and resources are available; it should rather be seen as a framework for fisheries that would otherwise have limited or no scientific management guidance.

The step-by-step process outlined in the toolkit is modeled after a framework that was applied in the conch and lobster fisheries of Belize (McDonald et al., 2017). A MSE of that particular framework has shown that it can act to maintain stable catches and prevent stock collapse, even when the fisheries are faced with environmental stochasticity and increasing effort (Harford et al., 2016). The toolkit was further refined for the Fish Forever partnership in the context of TURF-reserves in the developing tropics, and thus has a focus on input controls as management options as well as data types that are commonly found in this setting. However, the toolkit is broadly applicable to any type of small-scale fishery where these types of management options and data exist.

This paper aims to: 1) fully describe the process outlined in the AFAM Toolkit; and 2) apply the toolkit to a case study of Karimunjawa National Park, Indonesia (KNP) to illustrate how the toolkit can be used to inform management recommendations. The materials and methods section first outlines the AFAM Toolkit generally, including how to access the toolkit, stakeholders involved and skills required, data requirements, and the eight steps in the toolkit. Second, the materials and methods section introduces the case study site of KNP and the nine target species that are analyzed. KNP is a helpful example for using the toolkit in that it typifies many small-scale fisheries where data are limited, but where there is a need for improved management due to low compliance of existing regulations, high fishing pressure, and depleted stocks (Campbell et al., 2014, 2012). The results section outlines the results of the KNP toolkit application in a stepwise fashion. Finally, implications of the results are discussed, both in the context of KNP as well as in the broader context of how this framework can be used in other data- and resource-limited fisheries.

2. Materials and methods

2.1. AFAM toolkit overview

2.1.1. Accessing the toolkit

The complete toolkit can be used online (https://sfg-ucsb.shinyapps.io/afam-dashboard/), but can also be used offline by installing an open-source R package (https://github.com/SFG-UCSB/afamAppPackage). The dashboard is built using the R programming language (R Team, 2013) and R Shiny package (Chang et al., 2017), the guidance documentation is built using the R Bookdown package (Xie, 2016), and the R package is stored on the open-access code-sharing platform GitHub ("GitHub," 2017). Using the dashboard and guidance documentation online requires no understanding of R, a key feature to both the Shiny and Bookdown platforms. As a sample data set for learning the toolkit and also exploring the results from this paper, the dashboard comes pre-loaded with the data used in this paper. The fisheries science and management community is also encouraged to make contributions to the dashboard R package so that it can continually improve over time. The authors therefore hope that the toolkit can further advance the growing open-source and open-science movement (Dabbish et al., 2012; Wolkovich et al., 2012), particularly as it relates to data-limited fisheries assessment and management.

2.1.2. Stakeholders involved in using the AFAM toolkit

The toolkit facilitation should be led by one person who works with a multi-stakeholder group to reach consensus and make decisions. It is ideal if the facilitator has meeting facilitation experience, effective communication skills, and a general knowledge of fisheries management, ecology, population dynamics, and local policy. It can also be helpful if the facilitator is independent so as not to introduce bias into the process. The lead facilitator should coordinate a multi-stakeholder participatory process to work through all steps of the toolkit; this group may include fishers, managers, buyers, scientists, members of NGOs, and government officials. It is important that the entire adaptive management process be participatory in order to: 1) draw on the knowledge of scientists, resource users, government agencies, and others; 2) create common goals and a common understanding of the fishery; 3) create a context for learning together and working cooperatively; and 4) empower stakeholders with ownership of the process. This reduces uncertainty and conflict while increasing the likelihood of compliance with regulations generated by the adaptive management process. A group of individuals, such as a Technical Working Group, could be formed to work through these decisions.

2.1.3. Data requirements for the AFAM toolkit

The toolkit has minimum data requirements as well as additional data options that are recommended but not required (Table 1). The amount of available data will determine the tier for using the toolkit (see description of tiers in Step 1). At a minimum, it is necessary to have a qualitative understanding of the fishery and any spatial management characteristics, along with a list of prioritized species for management and general management goals. After stakeholders have articulated

Table 1
Minimum and recommended data for using the AFAM Toolkit.

Minimum Data Requirements	Recommended Additional Data Options
Qualitative characterization of the fishery (e.g., local history, gear types, target species, fishing locations, fishing seasons, existing regulations, etc.)	Fishery-dependent catch data for prioritized species
Spatial management characteristics, if relevant (e.g., TURF and/or Reserve size and location)	Fishery-dependent effort data for prioritized species
List of prioritized species for management	Fishery-dependent length-frequency data for prioritized species
List of general management goals (e.g., to reduce overfishing, to reduce habitat destruction, to increase food security, to improve income stability, to increase in-water species diversity and biomass for dive tourism, etc.)	Underwater visual survey data (density of prioritized species)
	Underwater visual survey data (total biomass of all fish species)

general management goals, the AFAM Toolkit helps these stakeholders determine how to achieve these goals through an adaptive FMP.

In the case of the KNP case study in this paper as well as other sites in the Fish Forever program, these data were collected through two accompanying toolkits, the Fisheries Landscape Assessment and Goal Setting (FLAGS) Toolkit (see Battista et al., 2016 for a description of one of the tools contained within this toolkit, focused on ecosystem risk assessment) (Battista et al., 2016) and the TURF-Reserve Design Toolkit (see Oyanedel et al., 2016 for a description of the bioeconomic model that forms the basis of this toolkit, focused on assessing tradeoffs between different spatial design options) (Oyanedel et al., 2016). However, other existing tools and informal processes can be used to collection this information in other fisheries contexts (e.g., the Participatory Coastal Resource Assessment (PCRA) in the Philippines) (Deguit et al., 2004).

2.2. Steps of the AFAM toolkit

Following a step-wise approach (Fig. 1), AFAM provides a framework to adaptively analyze data, evaluate the performance of the target fisheries, choose management controls, and adjust management so that the fisheries move towards sustainable management. Specifically, AFAM allows fisheries managers to: 1) select fisheries management controls (i.e., science-based regulations) designed to help managers achieve their fisheries goals (e.g., reduce overfishing, increase species diversity for tourism); 2) determine how data should be used to monitor and evaluate target species and ecosystem status over time using fishery performance indicators; 3) perform data-limited assessment methods to calculate performance indicators using a simple but powerful dashboard; and 4) define a process for how fisheries assessment and management will be reviewed and adapted periodically over time, using the best available scientific data and LEK. During each cycle of completing the steps, stakeholders should critically consider how well previous management actions moved them towards their objectives, and adaptively adjust tactics as necessary using this new knowledge.

2.2.1. Step 1 – determine assessment and management tier

The assessment and management tier is based on the data that is available and will determine which assessment and management options are available. Tier 1 in the AFAM Toolkit is designed for fisheries with little to no quantitative data; fisheries with one year or less of catch, length, and/or underwater visual survey data fall into Tier 2; and Tier 3 is designed for fisheries with two or more years of catch and/or length data (Fig. 2). Tier 1 provides precautionary management guidance using qualitative information on the fishery; Tier 2 allows for a snapshot of data-limited assessments from a single year of data and

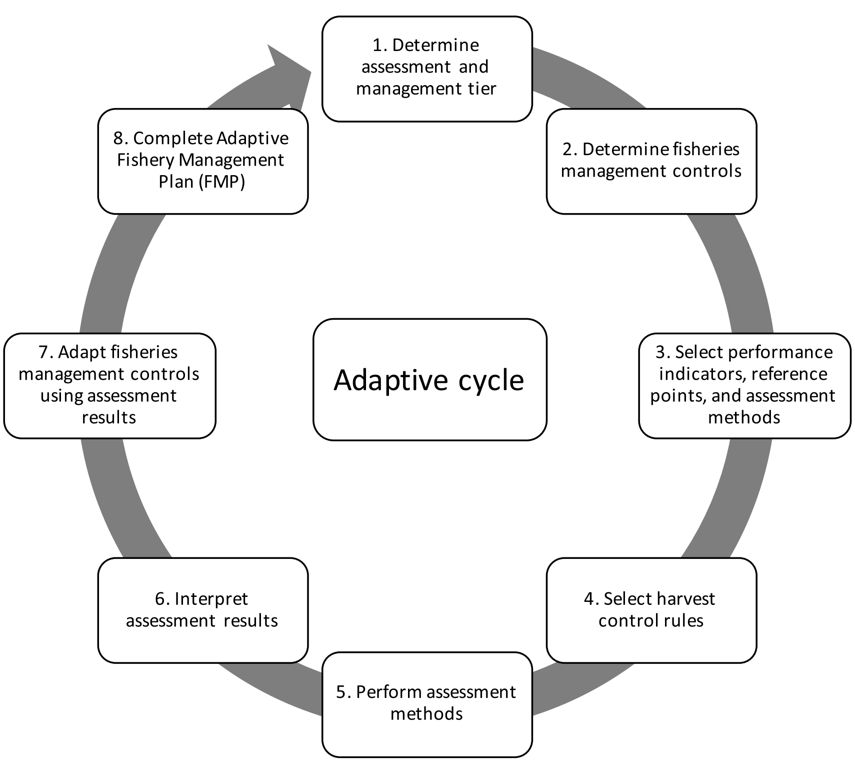

Fig. 1. AFAM Toolkit 8-step Schematic.

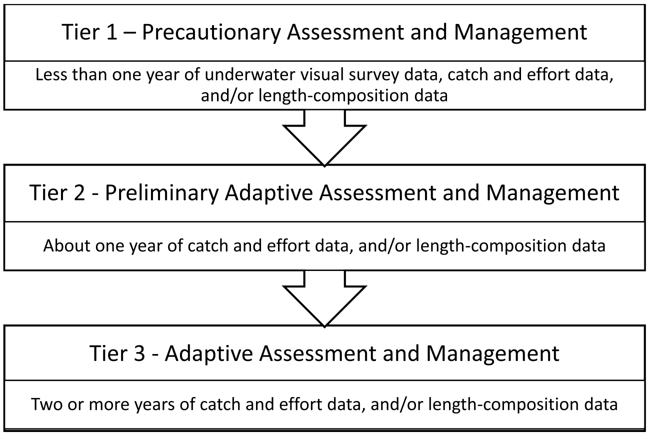

Fig. 2. Schematic of the AFAM Toolkit's three assessment and management tiers.

provides a larger range of management options; and Tier 3 allows for more refined trend analysis of empirical data and data-limited assessments over time, along with the largest range of management options (see Step 2 for a description of the management options for each tier). As the AFAM Toolkit is adaptively used at a site over time, the Assessment and Management Tier may progress from one level to the next as more data become available, presenting new assessment and management options. In Step 1 of the dashboard, users upload their available data, and their assessment and management tier is automatically calculated. These data will then be used during subsequent steps in the dashboard.

2.2.2. Step 2 – determine appropriate fisheries management controls

Fishery management controls allow managers to limit aspects of fishing behavior to reduce fishing mortality, protect sustainable size structure in the population, and/or protect key biological or ecological function. AFAM provides a framework for choosing appropriate fishery management controls based on the framework proposed by Liu et al. (2016). Nine potential management controls are included as options, with different controls appropriate for different tiers (Fig. 3). At a minimum, for Tier 1 sites with little to no data, AFAM provides several options: prohibiting the use of destructive fishing gear (i.e., dynamite, chemicals, fine mesh nets), spatial seasonal closures to protect known spawning aggregations, and seasonal or sex restrictions to protect gravid or egg-bearing females. These options can be informed by LEK and fisher engagement. Toolkit users first consult the following decision tree to determine an initial list of the types of fisheries management controls to consider (Fig. 3).

Once the decision tree produces an initial list, users refine the list by considering the goals of the fishery and evaluating the biological, ecological, and socioeconomic implications of each type of management control. The toolkit guidance documentation outlines potential impacts of fishery management controls on the following objectives: 1) biological objectives (protect spawning stock biomass; protect age-structure; and protect vulnerable life history stages); 2) ecological objectives (protect habitat; reduce bycatch and/or discards); and 3) socioeconomic objectives (increase fisher profits; increase product quality; maintain fishing efficiency; and promote fisher safety). Users crosswalk the specific goals of their fishery with how each management control might impact that goal. Additionally, users consider the feasibility of each type of management control in terms of data requirements and enforcement; guidance is provided that outlines these feasibility considerations for each type of management control. If fisheries management controls have been implemented in the past, users are directed to consider how well these controls worked in meeting fisheries objectives and if these controls are still appropriate or need adapting. Case studies of how management controls have been applied in small-scale fisheries are also provided in the documentation to inform toolkit users how controls could be implemented in their fishery. Once users have selected their fisheries management controls, they select these in the checkboxes shown in Step 2 of the dashboard. Only the options appropriate for the assessment and management tier determined in Step 1 are shown.

2.2.3. Step 3 – select performance indicators, reference points, and assessment methods

Performance indicators show how the fishery is performing relative to a reference point. They can either be model-based indicators that are calculated using simple models, such as fishing mortality, or empirical indicators that are calculated directly from the data, such as trends in catch. They can even be data-free indicators that are based on LEK, such as changes in species catch composition or season length. Reference points include a Target Reference Point (TRP), a desired state of the fishery, and a Limit Reference Point (LRP), a state that indicates

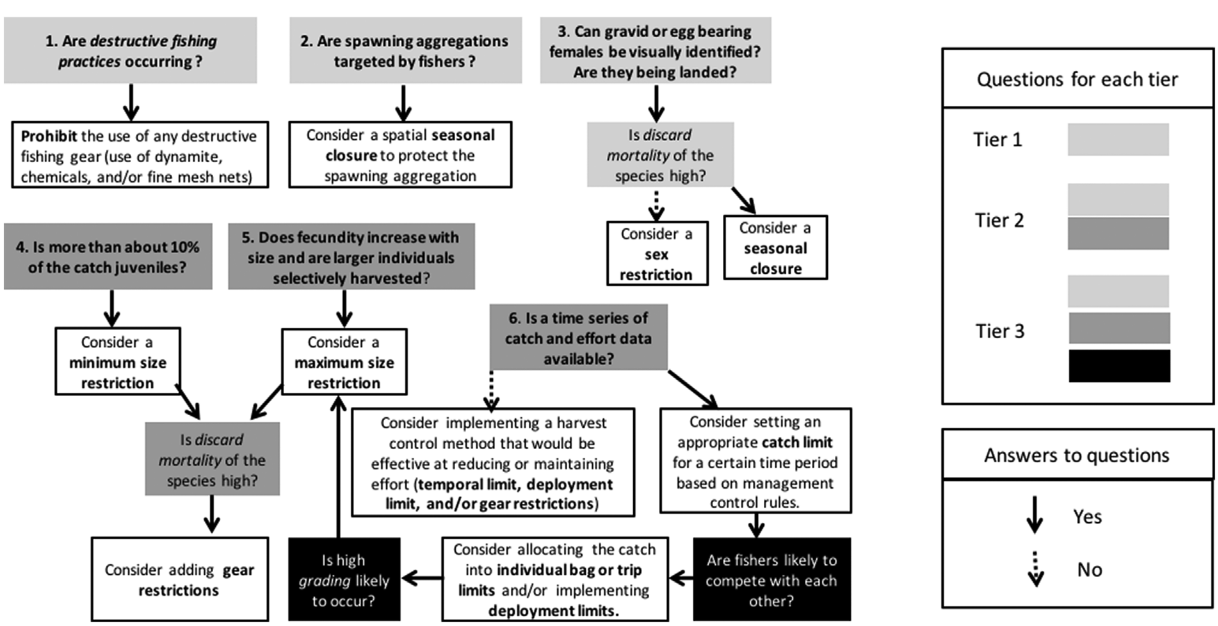

Fig. 3. Decision tree for selecting a preliminary list of appropriate fisheries management controls.

Table 2
Performance indicators, target reference points (TRPs), and limit reference points (LRPs) used for assessment of KNP target species, based on published best practices.

Performance Indicator (and assessment method)	Tier Use	Data Source	TRP	LRP	Reference
Presence of destructive fishing gear	1, 2, 3	LEK	No destructive fishing practices being used	Destructive fishing practices being used	–
Changes in length of fishing season	1, 2, 3	LEK	No changes in the fishing season	Significantly increased variability in fishing season, or decreased length of fishing season	–
Changes in caught species composition	1, 2, 3	LEK and life history information	No change in composition of caught species	Major change in composition of caught species (e.g, fewer species, more pelagics, fewer predators, increased grazers)	–
Species vulnerability	1, 2, 3	Productivity Susceptibility Analysis (PSA)	PSA score $\leq$ 2.0	PSA score $>$ 2.0	Patrick et al., 2010
Fished:Unfished Biomass Ratio (aggregated across all species) (Coral reef thresholds method)	1, 2, 3	Fishery-independent underwater visual survey data	0.5	0.25	McClanahan et al., 2011, Karr et al., 2015
Fished:Unfished Density Ratio (for target species) (Density ratio method)	1, 2, 3	Fishery-independent underwater visual survey data	0.6	0.2	Fujita et al., 2014, McGilliard et al., 2010, Babcock and MacCall, 2011
Fishing mortality/Natural mortality (F/M) (Catch Curve method)	2, 3	Fishery-dependent length-frequency data	1	2	Sparr and Venema, 1998, Kay and Wilson, 2012, Wayte and Klaer, 2010
Fishing mortality/Natural mortality (F/M) (Average length/LBAR) method)	2, 3	Fishery-dependent length-frequency data	1	2	Ault et al., 2005
Percent Mature in the catch (Froese method)	2, 3	Fishery-dependent length-frequency data	100	50	Froese, 2004
Percent Optimal in the catch (Froese method)	2, 3	Fishery-dependent length-frequency data	100	80	Froese, 2004
Percent Megaspawner in the catch (Froese method)	2, 3	Fishery-dependent length-frequency data	30	20	Froese, 2004
Spawning Potential Ratio (SPR) (Length-based SPR method)	2, 3	Fishery-dependent length-frequency data	0.4	0.2	Hordyk et al., 2014
Trend in CPUE	3	Fishery-dependent catch and effort data	Increasing over previous year or stable ($\geq$0% increase)	Decreasing rapidly below previous year ($>$ 50% decrease)	Little et al., 2011
Trend in Catch	3	Fishery-dependent catch data	Increasing over previous year or stable ($\geq$0% increase)	Decreasing rapidly below previous year ($>$ 50% decrease)	Little et al., 2011

imminent danger of fishery collapse. The assessment method is the technique for calculating performance indicators using available data.

The AFAM Toolkit includes 15 performance indicators that should apply in most data-limited contexts (Table 2) and provides guidance on the number and type of indicators that should be included based on the assessment and management Tier. For Tier 1, at least one indicator should be based on LEK; and if available, at least one indicator should come from a fishery-independent underwater visual survey. For Tier 2, at least one indicator should be based on a fishery-dependent length-composition survey; and if available, at least one indicator should come from a fishery-independent underwater visual survey. For Tier 3, all indicators from Tier 2 should be used alongside at least one trend-based indicator that uses a time series of landings or CPUE data. This is not an exhaustive list, so additional and/or alternative performance indicators and assessment techniques can be added within this framework, but would require users to build additional assessment modules, or use other modules from other sources.

Data availability is a driving factor in choosing performance indicators, but is not the only consideration in choosing performance indicators. All data-limited assessment methods have associated input parameter sensitivities (e.g., Babcock et al., 2013; Carruthers et al., 2014), caveats and critical assumptions; none provide a perfect representation of the fishery, and each could be misleading if certain assumptions are violated. The AFAM Toolkit provides details on the input parameter sensitivities and caveats associated with each assessment method; these should be carefully reviewed before selecting performance indicators. Given challenges with any one indicator, multiple indicators should be used from independent data sources with different sensitivities, if possible, so that the chance of multiple indicators failing simultaneously is minimized. Additionally, the dashboard includes a series of questions as a built-in safety check to prevent assessment methods from being used in situations where assumptions are clearly violated or data are insufficient.

Many of the data-limited assessment methods used by the AFAM toolkit rely on species-specific life history information as model inputs; these requirements are summarized in the toolkit for each method. It is during this step that the user should compile all relevant life history information. Wherever possible, parameters from local studies and fisheries should be used. Sources of these parameters can come from published scientific literature, unpublished grey literature, and online databases such as FishBase (Froese and Pauly, 2017). Moreover, wherever possible and economically feasible, fisheries managers should conduct life history studies to collect locally-relevant parameters for use in adaptive management. However, many data-limited fisheries lack local life history information on their target species or the resources to conduct new studies; there may therefore be a need to use life history parameters from populations of the same species that are nearby geographically. If using life history information from other fisheries, this should be considered when interpreting performance indicators and reference points. To aid in the collection of life history parameters, the dashboard comes pre-loaded with a database of parameters for many target species that are commonly found in Brazil, Philippines, and Indonesia, three of the first Fish Forever countries. If using information from the included life history database, users should first carefully check the parameters and included references to ensure they are reasonable for their fishery.

Once performance indicators have been determined, TRPs and LRPs for each performance indicator should be set. Table 2 provides suggested TRPs and LRPs for each performance indicator based on best practices from the literature and which are broadly applicable for many finfish species; these are also loaded as defaults in the dashboard. Length-based indicator reference points are based on either healthy size structures (i.e., Froese indicators) or proxies for MSY (i.e., fishing mortality and SPR indicators), while underwater visual survey indicators are based on proxies for healthy coral reef ecosystems. However, stakeholders should use discretion when setting reference points for their particular fishery. These could be adjusted based on the goals of the fishery; for example, if the primary goal of the fishery is to increase biomass in the water to support a dive tourism industry, a higher TRP for SPR may be preferred. Uncertainty and risk tolerance should also be considered, and may result in more conservative reference points based on stakeholder preferences. Where available, literature from nearby fisheries or similar target species should also be consulted to determine the most appropriate reference points. Finally, assessment methods are selected for each performance indicator. Most indicators have only one possible method, with the exception of fishing mortality/natural mortality which has two choices. Once users have selected their performance indicators, reference points, and assessment methods, they select these in the checkboxes shown in Step 3 of the dashboard. Only options that do not violate data requirements and major assumptions are shown.

2.2.4. Step 4 – define harvest control rules

A harvest control rule (HCR) helps stakeholders compare performance indicators with reference points and adjust fisheries management controls accordingly. For example, a harvest control rule may specify that if SPR is found to be below its associated TRP, the total allowable catch should be reduced by a previously agreed upon amount. It is important for stakeholders and managers to agree upon HCRs in a safe and neutral setting before data analysis or decision making. This can help improve compliance by ensuring management responses are objective, consistent, transparent, and appropriate. This can also help mitigate confirmation bias or conflicts of interest by certain stakeholders, since decisions will be agreed upon before any data is analyzed or any immediate stakes are at risk. Therefore, it is necessary to identify all foreseeable scenarios that could occur in the fishery using the given set of performance indicators and agree upon the likely interpretations leading to those scenarios and the appropriate management responses for each interpretation.

The output of this step is a HCR table that outlines all imaginable scenarios, possible interpretations, and management responses for each interpretation. Each scenario in the table is defined by a set of performance measures, one for each performance indicator. A performance measure indicates how each indicator is performing against its associated TRPs and LRPs. If only a single performance indicator is being included, only a single set of performance measures must be included in the HCR table (Table 3). However, if multiple performance indicators are included, all possible combinations of the associated performance measures should be included as their own unique scenarios (Table 4). The AFAM Toolkit translates these performance indicators into a simple traffic light color-coding system; green indicates desirable fishery performance (the PI is performing better than the TRP), Yellow indicates undesirable fishery performance (the PI is between the TRP and the LRP), and Red indicates the fishery is in danger of collapse (the PI is performing worse than the LRP). Green indicates that no management response is necessary or management could be less restrictive; yellow indicates that a precautionary or more restrictive management response should be implemented; and red indicates that the fishery should be closed and a fishery recovery plan implemented. The dashboard for Step 4 automatically creates a blank HCR table to be filled out by the

Table 3
Harvest control rule table for a framework with a single performance indicator.

Scenario	Performance Measure	Possible Interpretations	Management Response
1	Green	Interpretation A	Response A
		Interpretation B	Response B
2	Yellow	Interpretation A	Response A
		Interpretation B	Response B
3	Red	Interpretation A	Response A
		Interpretation B	Response B

Table 4
Harvest control rule table for a framework with two performance indicators.

Scenario	Performance Measures		Possible Interpretations	Management Response
	Performance Indicator 1	Performance Indicator 2		
1	Green	Green	Interpretation A	Response A
			Interpretation B	Response B
2	Green	Yellow	Interpretation A	Response A
			Interpretation B	Response B
3	Green	Red	Interpretation A	Response A
			Interpretation B	Response B
4	Yellow	Green	Interpretation A	Response A
			Interpretation B	Response B
5	Yellow	Yellow	Interpretation A	Response A
			Interpretation B	Response B
6	Yellow	Red	Interpretation A	Response A
			Interpretation B	Response B
7	Red	Green	Interpretation A	Response A
			Interpretation B	Response B
8	Red	Yellow	Interpretation A	Response A
			Interpretation B	Response B
9	Red	Red	Interpretation A	Response A
			Interpretation B	Response B

user which includes a row for each scenario and columns for performance measures, likely interpretations, and management responses.

When creating the HCR for each scenario, stakeholders must identify a set of possible interpretations that would explain why the fishery is experiencing a certain set of performance measures. In some cases, a particular performance measure or combination of performance measures will be associated with a unique interpretation of the fishery performance (McDonald et al., 2017; Prince et al., 2011). In other cases, a performance measure or combination of performance measures could be indicative of multiple possible interpretations of conflicting fishery performance. For example, if CPUE is increasing, this would indicate a generally positive trend; but if fish are getting smaller, this would indicate a generally negative trend. An alternative explanation could be that a more efficient gear such as fine-mesh net has been introduced, which could deplete the population while increasing CPUE in the short term. LEK is critical in identifying these types of fishery-specific possibilities. When multiple interpretations are possible, each possible interpretation should be listed in the table alongside an appropriate management response. The toolkit provides examples of interpretations and management responses for each performance indicator and associated performance measure. These examples have been drawn from the literature and collective knowledge of the co-authors. However, the provided examples are by no means exhaustive or prescriptive – they are illustrative only. It is the responsibility of the stakeholders involved in the process to outline the most likely interpretations that are likely to occur in their fishery, along with the most feasible management responses for responding to those interpretations. In situations of uncertainty or ambiguity, precautionary management responses should be employed.

Data collection methodologies may also impact likely interpretations. To correctly interpret analyses using fishery-dependent data, it is important to understand the history of the fishery (i.e., management changes, changes in fleet size, changes in gear types, changes in spatial distribution of fishing effort), as well as the design of data collection protocols (e.g., how data collection is stratified across time and space and across different gear types, fishers, and fleets). To correctly interpret fishery-independent data, is it also important to understand the history of the fishery, as well as sampling location design, species mobility, and any observation biases.

Finally, it is important to make HCRs as specific as possible; for example, if the performance indicator is 20% below the target reference point, the total allowable catch should be reduced by 20%. The magnitude that a HCR should adjust fishery management controls will depend on productivity and life history of the target species, likelihood of compliance, social and political feasibility, enforcement capacity, uncertainty of data and the estimation of performance indicators, size and ability of NTZs to buffer uncertainty, and risk tolerance. If HCRs have been implemented in the past, stakeholders should consider how well specific changes worked in improving performance measures and adaptively make adjustments as necessary.

2.2.5. Step 5 – perform assessment methods

During this step, users use the dashboard to calculate their performance indicators using the chosen assessment methods. The dashboard includes data visualization and assessment modules for all assessment methods included in the toolkit. Additionally, the guidance documentation provides further information on how each assessment method works, caveats, inputs and outputs, and assumptions. The catch curve assessment module utilizes the TropFishR R package (Sparr and Venema, 1998; Mildenberger et al., 2017), while the spawning potential ratio assessment modules utilizes the LBSPR R package (Hordyk, 2017; Prince et al., 2015).

2.2.6. Step 6 – interpret assessment results

Using the harvest control rule table defined in Step 4, stakeholders review assessment results, determine performance measures for each indicator, and select the most likely interpretation and appropriate management response. Step 6 of the dashboard provides a summary of all assessment results and performance measures. Interpreting these results will be very straightforward if only one possible interpretation was previously identified for the current scenario of performance measures. In the case where multiple interpretations are possible, it will be necessary to utilize stakeholder knowledge to select the most likely interpretation. The toolkit facilitator should be cautious of conflicts of interest, for example where stakeholders support certain interpretations that would indicate more positive fishery performance and therefore less restrictive management regulations (Mahon, 1997). If stakeholders cannot agree on the interpretation or are unsure, the most conservative interpretation and precautionary management response should be chosen. Once stakeholders have agreed upon an interpretation, users should record the interpretation in Step 6 of the dashboard.

2.2.7. Step 7 - adjust fisheries management controls using defined harvest control rules

The harvest control rules defined in Step 4 and the interpretations generated in Step 6 are used to adjust fisheries management controls appropriately. By this point, the appropriate management response has already been agreed upon during Step 4. Users should select the chosen management response in the drop-down menu in Step 7 of the dashboard.

2.2.8. Step 8 - complete your fishery management plan

Finally, the outputs of the AFAM Toolkit are used to complete a FMP for the fishery. Step 8 of the dashboard lets the user generate a PDF or Word Document summarizing all of the undertaken steps. This can form the basis of a new management plan. To complement this, the guidance documentation includes a broader FMP template that contains sections outlining an overview of the fishery, objectives and challenges, summaries of data, traditional knowledge, research that has been conducted on the fishery, details on monitoring and enforcement, and a description of the adaptive management framework. This template should be adapted for the local context of the fishery to be in compliance with any relevant regulations or norms.

2.3. AFAM toolkit application in Karimunjawa National Park

We used the methodology described above to assess and provide management recommendations for a number of target fisheries in Karimunjawa National Park (KNP) in Indonesia. Since KNP, Wildlife Conservation Society, and Rare have collected time series of catch, underwater visual survey, and length data for many target species, we were able to test all aspects of the toolkit, including the full suite of data-limited methods. The results of this process will be discussed in the Results section below.

2.3.1. Study site description

KNP is one of Indonesia's oldest marine national parks, encompassing 110,117 hectares of water and three coastal-marine ecosystems: coral reefs, seagrass and seaweed, and mangrove forests (Authority, 2016). Fishing is the primary livelihood for local residents (Jepara Regency in Figures - Statistics of Jepara Regency, 2015). Like all protected areas in Indonesia, KNP is zoned for multiple uses. The current zoning system includes four types of no-take zones, as well as rehabilitation zones, mariculture zones, religious and cultural zones, and traditional fishing zones, which enable the region's inhabitants to continue fishing using non-destructive practices. An additional traditional use zone, the Nyamuk Village Managed Area, was established as a TURF in May 2016. The TURF is managed by a group of community stakeholders including fishers, neighborhood representatives, elders, and religious leaders who are currently drafting a Management Plan. The TURF is approximately 800 ha in size, including a 150 ha no-take core zone, making this area a TURF-reserve.

Nine key target species represent a range of catch volumes, prices, and gear types (Table 5). These species were chosen since they are found frequently either in the underwater visual survey data, catch data, or both, and were also identified as important species for fishing livelihoods by the stakeholder working group described below. Catch volume, price, and gear type categories were determined using fishery-dependent landing site data collected at KNP in 2014. Catch volume is categorized by the annual catch normalized by the number of sampling trips, and is broken apart by the 33rd and 67th percentiles (High: > 5.75 kg/sampling trip; Medium: between 1.89 and 5.75 kg/sampling trip; Low: lower than 1.89 kg/sampling trip). Price is categorized by the ex-vessel price for each species, and is also broken apart by the 33rd and 67th percentiles (High: > 46,700 Indonesia Rupiah/kg; Medium: between 17,100 and 46,700 Indonesia Rupiah/kg; Low: lower than 17,100 Indonesia Rupiah/kg). Gear types are listed in descending order of the contribution of each gear type to catch volume.

Table 5
Key KNP target species including scientific name, common name, predominant gear type (s), relative catch volume, and relative price.

Scientific Name	Common Name	Catch Volume	Price	Predominant Gear Type(s)
Bolbometopon muricatum	Bumphead parrotfish	High	Low	Speargun
Caesio cuning	Yellowtail fusilier	High	Low	Speargun Trap Handline Trolling
Caranx ignobilis	Giant trevally	Medium	Medium	Handline Trap Trolling Speargun
Lutjanus gibbus	Humpback snapper	Medium	Medium	Handline Trap
Lutjanus malabaricus	Malabar snapper	High	Medium	Trap
Plectropomus areolatus	Spotted coral grouper	Low	High	Speargun Trap
Plectropomus leopardus	Leopard coral grouper	Low	High	Speargun Trap
Plectropomus oligacanthus	Vermicular grouper	Medium	High	Speargun Handline
Scarus ghobban	Blue-barred parrotfish	Low	Low	Speargun

2.3.2. Stakeholder working group and process for the KNP case study

To work through the AFAM Toolkit steps described above, a multi-stakeholder group was assembled. This group included fisheries scientists from partner organizations at the Environmental Defense Fund, Rare, and the University of California, Santa Barbara, the three founding partners of Fish Forever. These scientists guided the process and lead the analysis, while also bringing general expertise on the selection and interpretation of performance indicators and references points. The group also included staff from Wildlife Conservation Society and Rare, who have worked with KNP for a number of years and are implementing partners for Fish Forever. This staff brought expertise on the data collection methodologies used by KNP, as well as knowledge of the fisheries, important for both the analyses as well as interpretation of the results. Finally, staff members from KNP itself, another local implementing partner for Fish Forever, participated in the group. These staff members brought intimate knowledge of the history of the park and its fisheries, and were critical in interpreting results. Since this group was composed of members from Indonesia, the United States, and Mexico, this work was primarily done remotely over email exchanges and a series of Skype webinars. The team met in person in KNP in July 2016 to review and interpret preliminary fisheries assessment results. Working through the entire process took roughly two years, from late-2014 to early-2017. However, much of this time was spent learning about the most efficient ways to conduct this process as well as developing the toolkit itself. We anticipate that the toolkit presented in this manuscript would greatly improve the ease and speed of this process, while also reducing the need for the high level of outside-expertise used in the KNP case study.

3. Results

The step-by-step results of KNP case study are described below.

3.1. Step 1 of the AFAM toolkit – determine assessment and management tier

To determine the appropriate assessment and management tier, an inventory of data was conducted. Fishery-dependent landing site data has been collected since 2009 and includes effort, gear type, catch (by species), where fishers caught their catch (by zone and whether it was caught inside or outside KNP), and individual fish lengths and weights (Campbell et al., 2014, 2012; Figs. A1–A3). Additionally, fishery-independent underwater visual surveys have been conducted within KNP intermittently since 2005 (Figs. A4 and A5). Belt transects are located both in fished and unfished areas of KNP (Campbell et al., 2012), and divers record fish densities and lengths, which are later converted to biomass using length-weight relationships (Froese and Pauly, 2017). For the interpretation of results, fishery-independent indicators were selected from 2013 data and fishery-dependent indicators from 2014, the most recent data used in this analysis. Since multiple years of catch, length, and underwater visual survey data are available for KNP, the Tier 3 assessment and management was selected. This tier features the greatest array of assessment and management options, since trends in performance indicators can be observed.

Table 6
Existing fisheries management controls for KNP along with qualitative compliance level, specific regulatory mechanism, and suggested new fisheries management controls.

Species	Existing Fisheries Management Controls	Compliance Level	Regulatory Mechanism	Suggested New Fisheries Management Controls
All Species	Spatial zoning regulations including no-take zones	High	Ministry of Environment and Forestry Regulation No.56/2006 on Guidance in NP Zoning System Ministry of Environment and Forestry Regulation No.28/2011 on Nature Reserve Area and Nature Conservation Area	–
	Ban on destructive gear types (potassium, dynamite, muro-ami/drive-in set net, trawl, purse seine)	High	Ministry of Environment and Forestry Regulation No.56/2006 on Guidance in NP Zoning System	–
	Restricted access to Nyamuk Village Managed Area TURF (Nyamuk Village)	Medium	National Law No.6/2014 on Village	–
	No live coral trap fishing (Keumujan and Parang Villages)	Medium	Ministry of Environment and Forestry Regulation No.56/2006 on Guidance in NP Zoning System National Law No.6/2014 on Village	–
	Ban of nets with mesh size smaller than 1 inch (Kemujan Village)	High	National Law No.6/2014 on Village Government Regulation No.50/2015 on Empowerment of Small Fishermen and Small Fish Breeders	–
	Ban on compressor fishing for fishers from inside or outside KNP (Kemujan and Nyamuk Villages)	Low	National Law No.6/2014 on Village Government Regulation No.50/2015 on Empowerment of Small Fishermen and Small Fish Breeders	–
	Ban on compressor fishing for fishers from outside KNP (Parang Village)	Low	National Law No.6/2014 on Village Government Regulation No.50/2015 on Empowerment of Small Fishermen and Small Fish Breeders	–
	Ban of spearfishing (Parang Village)	Medium	National Law No.6/2014 on Village Government Regulation No.50/2015 on Empowerment of Small Fishermen and Small Fish Breeders	–
	Ban of fishing vessels larger than 10 GT from using active fishing gears within Karimunjawa Archipelago	High	Provincial Ministry of Maritime Affairs and Fisheries Decree No. 523/2487/X/2014 on Standard Operating Procedures for Surveillance and Enforcement of Karimunjawa Islands	–
Bolbometopon muricatum	No species-specific controls	–	–	Consider speargun regulation, such as ban of compressor fishing or minimum size limit Consider banning the trade and sale of this species to protect its ecological function
Caesio cuning	No species-specific controls	–	–	Consider precautionary speargun regulation, such as ban of compressor fishing or minimum size limit
Caranx ignobilis	No species-specific controls	–	–	Consider speargun regulation, such as ban of compressor fishing or minimum size limit Consider hook size regulation to prevent capture of juveniles with handline Consider bans on net fishing Consider a minimum length at capture limit Larger NTZs with better compliance, focusing on tourism zones, and surveillance from tourism operators
Lutjanus gibbus	No species-specific controls	–	–	Consider trap modifications to allow juveniles to escape Consider effort restrictions, such as limiting numbers of traps Consider regulation of hook size to prevent capture of juveniles with handline
Lutjanus malabaricus	No species-specific controls	–	–	Consider effort restrictions, such limiting numbers of traps Consider trap modifications to allow juveniles to escape Consider a Fishery Improvement Plan, certification scheme, or other supply chain interventions that may increase price while also incentivizing sustainable fishing practices

(*continued on next page*)

Table 6 (*continued*)

Species	Existing Fisheries Management Controls	Compliance Level	Regulatory Mechanism	Suggested New Fisheries Management Controls
Plectropomus areolatus	Ban of spearfishing (Karimunjawa Village)	Medium	National Law of Fisheries No. 31/2014	Consider extending species ban to other villages within KNP
	Sale of this species is prohibited (Nyamuk Village)	Medium	Government Regulation No.50/2015 on Empowerment of Small Fishermen and Small Fish Breeders	Consider extending spearfishing ban to other villages within KNP Consider effort restrictions, such as limiting trap numbers
	Minimum weight of 300 g	Low	National Law No.6/2014 on Village	Consider trap modifications to allow juveniles to escape Consider hook size regulation to prevent capture of juveniles with handline
Plectropomus leopardus	Minimum weight of 300 g	Low	National Law of Fisheries No. 31/2014 Government Regulation No.50/2015 on Empowerment of Small Fishermen and Small Fish Breeders National Law No.6/2014 on Village	Consider speargun regulation, such as ban of compressor fishing or minimum length at capture limit
Plectropomus oligacanthus	Minimum weight of 300 g	Low	National Law of Fisheries No. 31/2014 National Law No.6/2014 on Village	Consider speargun regulation, such as ban of compressor fishing or minimum length at capture limit
Scarus ghobban	No species-specific controls	–	–	Consider speargun regulation, such as ban of compressor diving or minimum length at capture limit

3.2. Step 2 of the AFAM toolkit – determine fisheries management controls

Table 6 summarizes existing fisheries management controls. Some of these controls apply to all species, while several apply only to specific species. Additionally, some controls only apply in certain villages – these are denoted in parentheses. Qualitative compliance levels based on stakeholder knowledge are provided for each control, as well as the regulatory mechanism where the control is codified. The current focus of management in KNP is to strengthen these existing controls, although the AFAM Toolkit generated new fisheries management control options for each species later in Step 4 through 6 – these suggested new controls are also included in this table. In addition to the management responses outlined in this table, an overarching management response for all species should be continued enforcement and increased community awareness of KNP's TURF-reserve system, which can be used to manage entry and effort for all species.

3.3. Step 3 of the AFAM toolkit - select performance indicators, assessment methods, TRPs, and LRPs

Because KNP falls into Tier 3, all AFAM performance indicators from Table 2 can be used. For each performance indicator, TRPs and LRPs were selected based on best practices from the literature and as recommended in the AFAM Toolkit (Table 2). To inform the indicators, life history information was gathered for KNP's nine key target species through a comprehensive literature review (Table A1). Unfortunately, no local KNP life history studies exist for these species. For example, the growth parameters used to assess the status of *Plectropomus areolatus* in KNP came from an otolith study in the Torres Strait, about 2000 miles away (Williams et al., 2008). These parameters may in fact vary significantly from the growth parameters of coral groupers in Karimunjawa. Length-based indicators are therefore used with caution, and compared with indicators from other data sources and validated with LEK.

3.4. Step 4 of the AFAM toolkit – define harvest control rules

The current focus of KNP management is to strengthen existing fisheries management controls (Table 6). Therefore, formal harvest control rules have not yet been created that define how management should change given a certain interpretation of the fisheries assessments. HCRs may eventually be defined in the future. For now, stakeholders simply used the default HCR guidance included in the toolkit as a starting point to consider possible interpretations and suggested management actions for each species.

3.5. Step 5 of the AFAM toolkit - perform assessment methods

For this step, the AFAM Toolkit dashboard was used to calculate all performance indicators. Trends in catch and CPUE, as well as the ecosystem level Fished:Unfished Biomass Ratio, were calculated for all species. Only four species had sufficient underwater visual survey data for calculating species-level Fished:Unfished Density Ratio. Length-data from 2014 were used to calculate all three Froese indicators for all species. However, only two species (*Caesio cuning* and *Lutjanus gibbus*) had more than 500 length measurements in 2014; and of these, only one had a unimodal normal distribution indicative of equilibrium conditions (*Caesio cuning,* Fig. A1). Therefore, fishing mortality and spawning potential ratio were only calculated for *Caesio cuning*. Once each performance indicator was calculated, it was compared against its associated TRPs and LRPs to determine its performance measure.

Table 7 shows the raw numerical assessment results for all performance indicators and priority species. The numerical value for the performance indicator is given, and each cell is color-coded using a traffic light system which represents each indicator's performance

Table 7
Assessment results for each species and performance indicator including the numeric value and traffic light color coding representing the performance measure for each.

Species	Catch Trend (%)	CPUE Trend (%)	Biomass Ratio	Density Ratio	F/M (Catch Curve)	F/M (LBAR)	Percent Mature	Percent Mega	Percent Optimal	SPR
Bolbometopon muricatum	97.2 (Green)	26.92 (Green)	1.24 (Green)	0.43 (Yellow)	-	-	23.33 (Red)	1.67 (Red)	10 (Red)	-
Caesio cuning	-20.79 (Yellow)	-4.76 (Yellow)	1.24 (Green)	1.3 (Green)	1.63 (Yellow)	2.29 (Red)	99.29 (Yellow)	5.51 (Red)	7.07 (Red)	0.24 (Yellow)
Caranx ignobilis	-22 (Yellow)	-31.03 (Yellow)	1.24 (Green)	-	-	-	5.26 (Red)	0 (Red)	0 (Red)	-
Lutjanus gibbus	87.68 (Green)	60.53 (Green)	1.24 (Green)	-	-	-	75.15 (Yellow)	87.43 (Green)	11.08 (Red)	-
Lutjanus malabaricus	74.4 (Green)	-38.1 (Yellow)	1.24 (Green)	-	-	-	100 (Green)	78.05 (Green)	21.95 (Red)	-
Plectropomus areolatus	-55.3 (Red)	-52 (Red)	1.24 (Green)	1 (Green)	-	-	38.1 (Red)	23.8 (Yellow)	41.6 (Red)	-
Plectropomus leopardus	-13.25 (Yellow)	-37.69 (Yellow)	1.24 (Green)	-	-	-	65.79 (Yellow)	34.21 (Green)	23.68 (Red)	-
Plectropomus oligacanthus	5.89 (Green)	-34.43 (Yellow)	1.24 (Green)	-	-	-	15.96 (Red)	2.13 (Red)	4.26 (Red)	-
Scarus ghobban	38.93 (Green)	-16.34 (Yellow)	1.24 (Green)	0.61 (Green)	-	-	90.48 (Yellow)	19.05 (Red)	33.33 (Red)	-

measure. Any cells marked with a hyphen ("-") had insufficient data.

3.6. Step 6 of the AFAM toolkit - interpret assessment results

Stakeholders worked through assessment interpretations one species at a time. For each species, stakeholders discussed the history of the fishery and their general impression of its conditions. Stakeholders talked through several likely interpretations using the AFAM Toolkit as a guide. While Step 4 of the Toolkit has not yet been used to create formal harvest control rules for KNP, the toolkit guidance documentation provides many possible interpretations and suggested management responses for all included performance indicators. In this way, the AFAM Toolkit spurred conversation and provided a structured way to think about this process, rather than providing prescriptive recommendations. Once the group had agreed upon an interpretation for each fishery, suggested management responses were generated and the feasibility of each management response was discussed in the context of KNP. Using the assessment results from Table 7 and the list of current and proposed fisheries management controls from Table 6, Table 8 shows the stakeholder-derived interpretations, suggested management responses, and feasibility of management response implementation for each target species.

While it may have been possible for stakeholders to arrive at some of these interpretations without looking at the data and simply relying on LEK, the use of quantitative data-limited methods did reveal patterns that may not have otherwise been observed, such as the beginnings of stock recovery for *Caesio cuning* and *Lutjanus gibbus*, as well as the danger of hyperstability for *Bolbometopon muricatum, Lutjanus malabaricus,* and *Plectropomus oligacanthus*.

3.7. Step 7 - adjust fisheries management controls using defined harvest control; and step 8 - complete your fishery management plan

Steps 7 and 8 have not yet been completed by KNP, and the suggestions contained in this paper have not yet been formally integrated into a FMP. Recent effort and capacity in KNP has been focused on implementing rights-based managed access through the creation of a TURF-reserve. However, it is hoped that results from Steps 1–6 above will eventually be used to inform the management regulations and an adaptive FMP within this TURF-reserve.

4. Discussion

One of the most important features of the AFAM toolkit is that it guides fishing communities through a participatory process of developing fisheries management rules based on ecological and socioeconomic goals. While the toolkit does not automatically prescribe specific fisheries management controls, performance indicators, reference points, or harvest control rules, it provides a structured approach for communities to compile the necessary information and make these decisions themselves. A key feature of the AFAM Toolkit is the flexibility to use the toolkit with any amount of data, different types of data, and varying levels of technical capacity. Another key feature is that the collaborative nature of the toolkit provides opportunities to incorporate LEK into management decisions. Stakeholder LEK can provide important insight into local conditions, stock statuses, and patterns in landings that may otherwise not surface in the performance indicators themselves (Aswani and Hamilton, 2004). Participatory adaptive management also provides an opportunity to build technical, scientific, and leadership capacity in local communities which may help to sustain co-management in fisheries in the long term and may improve the ecological and socioeconomic outcomes of management interventions and reduce non-compliance (Evans et al., 2011; McCay et al., 2014; Wamukota et al., 2012). The toolkit was built on the foundation of adaptive management so that assessments, interpretation, and management decisions can be revisited over time as more information and data become available and as environmental, social, and economic conditions change.

Inherent in any data-limited assessment initiative is the need to

Table 8
Stakeholder-derived interpretations, suggested management responses, and feasibility of management response implementation for each species.

Species	Interpretation	Suggested Management Response	Feasibility of Implementation
Bolbometopon muricatum	High fishing pressure and increasing gear efficiency with the use of spearguns has led to depleted population while temporarily maintaining catch and CPUE; this could be a case of hyperstability.	Consider speargun regulation, such as ban of compressor fishing or minimum size limit	Could be coordinated with the Provincial Fisheries Agency, KNPA and Karimunjawa Village governments.
		Consider banning the trade and sale of this species to protect its ecological function	Would be difficult since there are currently no regulatory mechanisms in place; KNPA could play role in socializing this idea
Caesio cuning	The stock is likely experiencing fishing pressure that is too high. However, due to its fast-growing nature, it is likely on a positive trajectory and has recovered somewhat since the ban of muro-ami nets in 2011 and the transition to spearguns and handlines.	Consider precautionary speargun regulation, such as ban of compressor fishing or minimum size limit	Could be coordinated with the Provincial Fisheries Agency, KNPA and Karimunjawa Village governments.
Caranx ignobilis	High fishing pressure has led to depleted population	Consider hook size regulation to prevent capture of juveniles with handline	Could be coordinated with the Provincial Fisheries Agency, KNPA and Karimunjawa Village governments.
		Consider hook size regulation to prevent capture of juveniles with handline	Would be difficult since there are currently no regulatory mechanisms in place; KNPA could play role in socializing this idea
		Consider bans on net fishing	Would be difficult since there are currently no regulatory mechanisms in place; KNPA could play role in socializing this idea
		Consider a minimum length at capture limit	Would be difficult since there are currently no regulatory mechanisms in place; KNPA could play role in socializing this idea
		Larger NTZs with better compliance, focusing on tourism zones, and surveillance from tourism operators	Would be straightforward to implement as part of the re-zoning process that happens every 5 years
Lutjanus gibbus	Stock is doing fairly well, but may be experiencing slight overfishing	Consider trap modifications to allow juveniles to escape	Could be coordinated with the Provincial Fisheries Agency (Act No.1/2014), although this act is not yet fully enacted
		Consider effort restrictions, such as limiting numbers of traps	Would be difficult since there are currently no regulatory mechanisms in place; KNPA could play role in socializing this idea
		Consider regulation of hook size to prevent capture of juveniles with handline	Would be difficult since there are currently no regulatory mechanisms in place; KNP Authority could play role in socializing this idea
Lutjanus malabaricus	Increasing export demand has led to increased targeting and decrease in size structure as fishery has become more depleted. Serial depletion or hyperstability could be causing increases in catch and CPUE.	Consider effort restrictions, such limiting numbers of traps	Would be difficult since there are currently no regulatory mechanisms in place; KNPA could play role in socializing this idea
		Consider trap modifications to allow juveniles to escape	Could be coordinated with the Provincial Fisheries Agency, KNPA and Karimunjawa Village governments
		Consider a Fishery Improvement Plan, certification scheme, or other supply chain interventions that may increase price while also incentivizing sustainable fishing practices	Could be coordinated with the Provincial Fisheries Agency, KNPA and Karimunjawa Village governments
Plectropomus areolatus	Increasing export demand has led to increased targeting and a depleted fishery.	Consider extending species ban to other villages within KNP	Would be difficult since there are currently no regulatory mechanisms in place; KNPA could play role in socializing this idea
		Consider extending spearfishing ban to other villages within KNP	Could be coordinated with the Provincial Fisheries Agency (Act No.1/2014), although this act is not yet fully enacted
		Consider effort restrictions, such as limiting trap numbers Consider trap modifications to allow juveniles to escape	Would be difficult since there are currently no regulatory mechanisms in place; KNPA could play role in socializing this idea
		Consider trap modifications to allow juveniles to escape	Could be coordinated with the Provincial Fisheries Agency (Act No.1/2014), although this act is not yet fully enacted
		Consider hook size regulation to prevent capture of juveniles with handline	Would be difficult since there are currently no regulatory mechanisms in place; KNPA could play role in socializing this idea
Plectropomus leopardus	Increasing export demand has led to increased targeting and a depleted fishery. Ban on nets since 2011 may have helped, but gears are getting more efficient with transition to speargun	Consider speargun regulation, such as ban of compressor fishing or minimum length at capture limit	Could be coordinated with the Provincial Fisheries Agency, KNPA and Karimunjawa Village governments
Plectropomus oligacanthus	Increasing export demand has led to increased targeting and a depleted fishery. Serial depletion or hyperstability could be causing increases in catch and CPUE. Ban in net since 2011 may have helped, but gears are getting more efficient with transition to speargun	Consider speargun regulation, such as ban of compressor fishing or minimum length at capture limit	Could be coordinated with the Provincial Fisheries Agency, KNPA and Karimunjawa Village governments
Scarus ghobban	This species is mostly caught for local consumption and is likely experiencing fairly low fishing pressure	Consider speargun regulation, such as ban of compressor diving or minimum length at capture limit	Could be coordinated with the Provincial Fisheries Agency, KNPA and Karimunjawa Village governments

ensure that assumptions associated with each assessment approach are not violated and that sensitivities to life history parameters are considered. Methods used to calculate fishing mortality and SPR assume constant natural mortality across size classes and are extremely sensitive to the natural mortality life history parameter which can be difficult to estimate in practice (Hordyk et al., 2014; Hoenig et al., 2016). These methods also assume equilibrium conditions, which may not be appropriate if recent management changes, environmental regime changes, or changes in gear selectivity or catchability have taken place. They also assume length data reliably track population size structure changes, and thus may be less accurate for small, fast-growing species. The Froese indicators are sensitive to life history parameters and selectivity, and may not always indicate the sustainability of the stock when used alone (Cope and Punt, 2009). The density ratio and coral reef threshold methods assume that a fully-functioning and well-enforced NTZ has been sited appropriately with representative habitat inside and outside of the NTZ, and has been in place long enough for the population living inside the NTZ to be a proxy for an un-fished population (Fujita et al., 2014; McGilliard et al., 2010; Babcock and MacCall, 2011). Biases can also occur with fishery-independent performance indicators due to survey design, site selection, number of transects within a survey, transect size, and observer biases (Floeter et al., 2005; Sale and Sharp, 1983; Holt et al., 2013; St John et al., 1990; Thresher and Gunn, 1986). Underwater visual surveys may also be unreliable for schooling or highly mobile species (Floeter et al., 2005). Simpler indicators can also be used, such as empirical trends in catch and/or CPUE that are observed directly from the data. However, CPUE may not be proportional to abundance over a whole exploitation history and an entire geographic range, because numerous factors affect catchability such as changes in gear type and efficiency. Catch trends can also be misleading if recent management or gear changes have taken place. The AFAM Toolkit therefore outlines the assumptions and challenges with each performance indicator and assessment technique within the toolkit. By systematically reviewing this information, stakeholders can better understand strengths and weakness with each approach and choose the most appropriate methodology for their fishery.

It is also necessary to use the best-available life history information in each assessment method and understand the implications of borrowing life history information from other regions or fisheries. Life history parameters can vary across geographic regions and environmental gradients, such that different populations of the same species may have different life history parameters (Gust et al., 2002). This spatial variation in the parameters can lead to uncertainty in what value is most appropriate for a specific fishery. While the current AFAM Toolkit does not incorporate uncertainty in life history parameters into calculations of performance indicators, this feature could be an area of future work.

Integrating multiple performance indicators into a single interpretation of fishery performance remains one of the greatest challenges of a multi-indicator framework like AFAM. This challenge is exacerbated when the indicators yield conflicting messages, as was the case with target species in KNP. There are generally two methods of reconciling these conflicts: 1) qualitative integration relying on LEK, as is outlined in this toolkit, and 2) quantitative integration relying on statistical methods or weighted scoring. With qualitative integration, stakeholders' LEK can verify if the relationship between the various performance indicators and their reference points is consistent with their knowledge of the fishery. In the case of indicators with conflicting messages, this knowledge is leveraged to resolve contradictions with a unique interpretation of fishery performance (McDonald et al., 2017; Prince et al., 2015). Local knowledge about management and gear history can inform which interpretation is more likely. LEK was critical during the interpretation process of the KNP case study in helping to explain why several species are experiencing increasing CPUE but showing poor performance across the length-based indicators (i.e., *Caesio cuning*, *Plectropomus leopardus*, and *Plectropomus oligacanthus*). For several of these species, stakeholders believe that continued high fishing pressure has led to depleted populations but a transition to efficient spearguns is driving increased CPUE, a situation that warrants precautionary management. A number of quantitative methods also exist for statistically integrating multiple indicators (Petitgas, 2009; Pitcher and Preikshot, 2001). An additional middle-ground approach could be to weight each performance measure and combine the measures into a single score indicative of fisheries performance (Harford et al., 2016). However, this toolkit purposefully avoids this approach for several reasons. Given the uncertainties in each of the data-limited assessments included in the toolkit, simply averaging or weighting performance measures into a single value might give toolkit users false certainty that this single value is absolutely correct, which could lead to less precautionary management recommendations. Additionally, providing this sort of single value could mask problems in the fishery that could otherwise be elucidated through stakeholder discussion and local ecological knowledge, which could lead to sub-optimal or even detrimental management recommendations. For example, if a two-indicator framework shows that average length is increasing and catch is increasing, these two generally positive measures would indicate positive fisheries performance if they were simply quantitatively weighted and combined into a single score. This would be an accurate representation if the fishery were actually recovering, but increasing average length and increasing catch could also be the result of increasing effort and expansion into deep water fishing grounds where larger fish are present, a situation that would in fact warrant concern and very different management recommendations, but would only be elucidated by a group of stakeholders familiar with the fishery. Finally, while formal Management Strategy Evaluation can be used to evaluate if an averaging or weighting approach could perform well for a particular fishery (e.g., the Harford et al., 2016 case study), this highly technical modeling approach is beyond the technical capacity of most small-scale fisheries for which the toolkit is designed. For these reasons, the toolkit purposefully does not include a quantitative approach for averaging or weighting of performance measures, but rather relies on LEK for interpretation of multiple measures and recommends precautionary management in situations of uncertainty or ambiguity.

Another area of future research could include simulations or analyzing empirical evidence to demonstrate the efficacy of the framework. Simulations using a management strategy evaluation (MSE) for particular fisheries could highlight biases and input sensitivities, identify the circumstances when one or several data-limited assessment methods could be consistently wrong and lead to misguided interpretations, and determine how well synthesizing certain combinations of indicators works in providing an objectively accurate interpretation of fishery performance. Previous MSE work has demonstrated that this type of adaptive management framework is expected to maintain stable catches and prevent stock collapse when equally weighting a suite of empirical indicators from independent data sources such as trends in catch, CPUE, and fishery-independent survey of abundance (Harford et al., 2016). Another area of future work could include evaluating empirical data from a fishery where the AFAM Toolkit framework is employed, such as KNP, to track how well the fishery performs over time and whether management goals are achieved.

Although the AFAM Toolkit has not yet been fully implemented into KNP's FMP, it has been a valuable tool in illuminating challenges in the fisheries and generating potential new directions for management. Length-based indicators for many species suggest that the size structures of the populations have been truncated by historical overfishing. However, seven of nine species show an increasing trend in catch and six of nine species show an increasing trend in CPUE. While there is no counterfactual or control site, this is encouraging evidence that broadly suggests recent conservation intervention management changes may be working to gradually improve fishery conditions. These interventions included bans on muroami (a type of destructive net which is driven into the reef) in 2010, a rezoning of the park in 2012 which established more no-take areas, and new village regulations designed to promote sustainable fishing practices that were implemented from 2012 onwards. In 2015, based on interpretations of the data collected up until 2014, the Karimunjawa National Park Authority, village communities, and NGOs facilitated development of a uniform set of regulations for adoption throughout the park. This included improved community compliance with no-take areas and bans on blast fishing, cyanide use, and the use of large nets such as muroami and purse seine.

Despite this encouraging evidence from KNP, precaution should still be exercised due to a number of challenges. For example, while most life history parameters came from the coral triangle region, some did not, and none came from KNP. Additionally, all fishery-dependent data come from landing sites in Karimunjawa village, just one of four fishing villages within KNP. These challenges may bias any single indicator, necessitating the use of multiple indicators to corroborate performance, and also precautionary management responses in the face of uncertainty. Finally, while the toolkit successfully helped a group of stakeholders assess the KNP fishery and provide management recommendations, this information still needs to be incorporated into a formal FMP, a practical challenge of translating science into action. A formal FMP could help the fishery status of KNP by reducing effort through the TURF-reserve system and also increasing selectivity and size of first capture of certain species through gear restrictions or size limits, allowing size structures to rebuild and populations to further rebound.

The toolkit was also piloted at sites in Brazil and the Philippines which had much less data than KNP, revealing the toolkit's value in contexts that are even more data-limited. In the case of six sites in Brazil, about one year of length data were available, meaning these sites were Tier 2 and that a number of length-based performance indicators could be calculated for each site. These indicators showed that in general, overfishing and catch of immature individuals was likely a problem at some sites, informing the need for more effective protection of population size structures through the use of increased mesh sizes, minimum size limits, and protection of nursery grounds. In the case of four sites in the Philippines, less than one year of length or catch data were available, meaning these sites were only Tier 1. Even without much data, using the toolkit facilitated the selection of precautionary management recommendations including better enforcement of existing regulations (e.g., ban on dynamite fishing) and protection of seasonal spawning aggregations based on LEK. Despite the lack of significant amounts of data for both the Brazil and Philippines study sites, the toolkit was still valuable by providing preliminary management recommendations, as well as helping site managers and stakeholders better understand the importance of setting up a more comprehensive data collection program and how these data could be used to directly inform more refined management decisions in the future.

5. Conclusion

The Adaptive Fisheries Assessment and Management Toolkit packages tools and methodologies into a guided process that allows managers to readily assess and manage their fishery. An open-source dashboard and step-by-step user guide provides stakeholders with resources to design their own adaptive management framework and calculate appropriate performance indicators for use in the framework. When using the toolkit, certain challenges persist that are relevant to many data-limited assessment applications, including imperfect sampling, uncertainty in life history parameters, and key assumptions in data-limited models. However, the AFAM Toolkit mitigates some of these challenges by including multiple performance indicators that can be used to triangulate an interpretation of fishery performance when informed by local ecological knowledge. It also provides an adaptive framework that improves over time and can be used to monitor trends, even in the face of biases and uncertainties. While the AFAM Toolkit is not meant to replace traditional stock assessment and management approaches, it can provide a way forward for places where those approaches are currently infeasible. The dashboard can be found online (https://sfg-ucsb.shinyapps.io/afam-dashboard/), or downloaded as an R package for local use (https://github.com/SFG-UCSB/afamAppPackage). The authors hope that the dashboard can contribute to the open-science movement for the benefit of data-limited small-scale fisheries.

The toolkit was used to assess the current performance of nine of the most important fisheries within Karimunjawa National Park, Indonesia. Even with challenges around data sources and performance indicators, the multi-indicator framework was used in tandem with stakeholder LEK to determine the most probable interpretations of fishery performance. For most species, the calculated performance indicators and interpretations show signs that high fishing pressure has likely led to depleted populations and truncated size structures, although some stocks are showing signs of recovery since recently applied management interventions. Moreover, these interpretations were used within the toolkit's framework to determine suggested management responses, which include regulation of the speargun and trap fisheries to be more selective, minimum size limits and the use of larger hook sizes to prevent capture of juveniles, and decreased fishing effort through spatial property rights and the established TURF-reserve system. The authors are hopeful that these recommendations will be considered when developing a KNP FMP. Given the toolkit's ability to translate small-scale fisheries data directly into management responses, it has broad applicability to other fisheries within Indonesia as well as small-scale fisheries more broadly.

Acknowledgements

We thank the Waitt Foundation, MacArthur Foundation, and Fish Forever (a partnership between Rare, Sustainable Fisheries Group, and Environmental Defense Fund) for their generous financial support of this project. We would also like to thank Bloomberg Philanthropies for supporting Rare's fisheries reform work in the Philippines and Brazil, where the Adaptive Fisheries Assessment and Management Toolkit was also tested. We thank Wildlife Conservation Society, Rare, and Karimunjawa National Park for providing all data used in this analysis. We also thank Lennon Thomas and Morgan Visalli for their help in developing components of the toolkit and Arwandrija Rukma for their help in understanding the regulatory framework of Karimunjawa National Park. We would like to acknowledge and thank Sarah Valencia for designing the original Microsoft Excel workbook that forms a partial basis for the inspiration behind the AFAM Toolkit. We would also like to acknowledge Tobias K. Mildenberger, Marc H. Taylor, and Matthias Wolff for developing the TropFishR R package, and Adrian Hordyk for developing the LBSPR R package, both of which the AFAM Toolkit dashboard utilizes for two of its assessment modules. We would like to thank several anonymous reviewers for providing thoughtful and constructive feedback on the manuscript. Finally, we would like to thank the many individuals from the Fish Forever global team, country teams, and implementing partners for their hard work in piloting the toolkit and providing thoughtful and constructive feedback.

Appendix

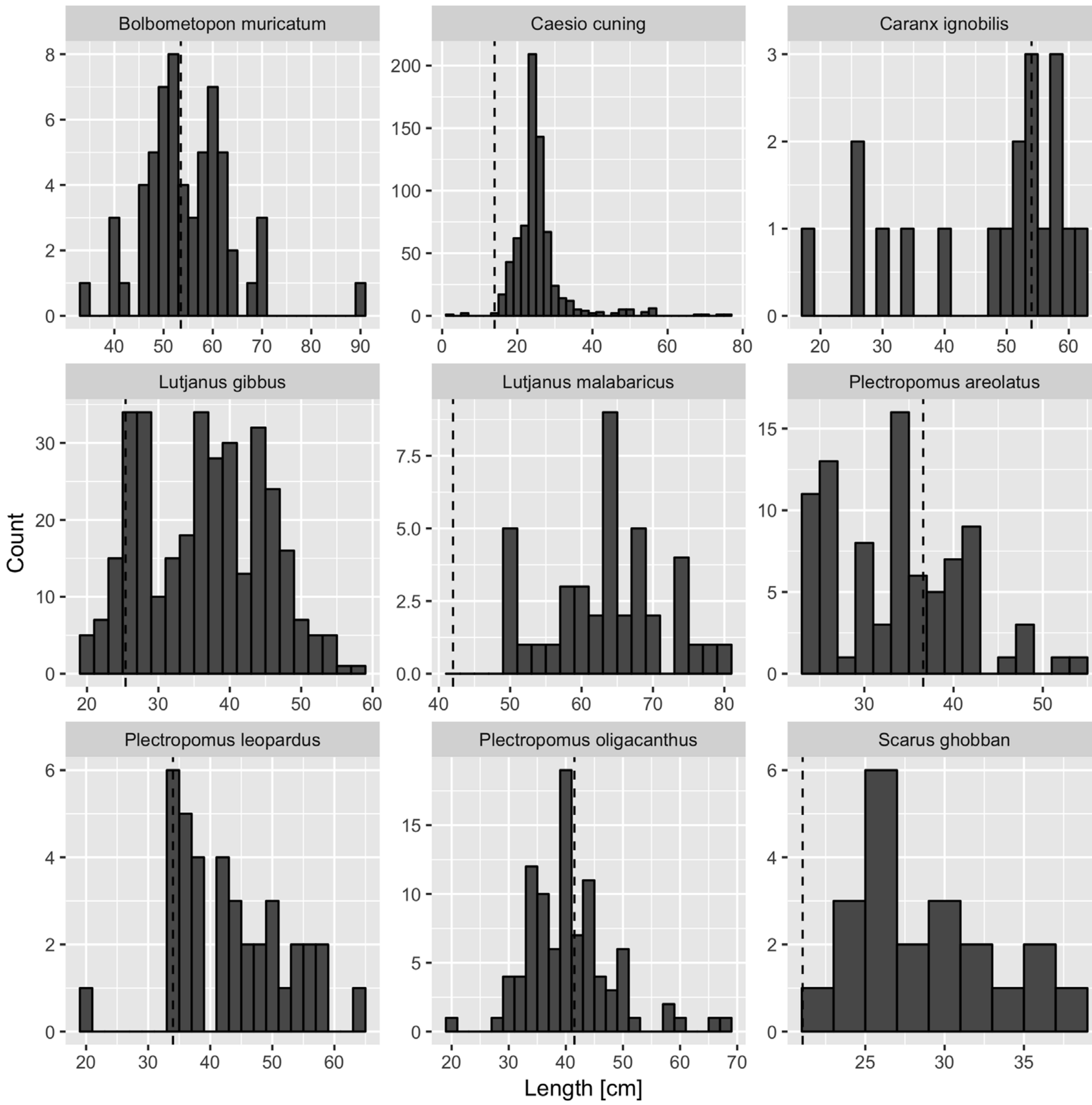

Fig. A1. Fishery-dependent length-frequency histograms for each species in 2014 in KNP, bin size of 1 cm. Data are aggregated across all management zones within KNP and across all gear types. Length at 50% maturity is shown for each species as a vertical dashed line.

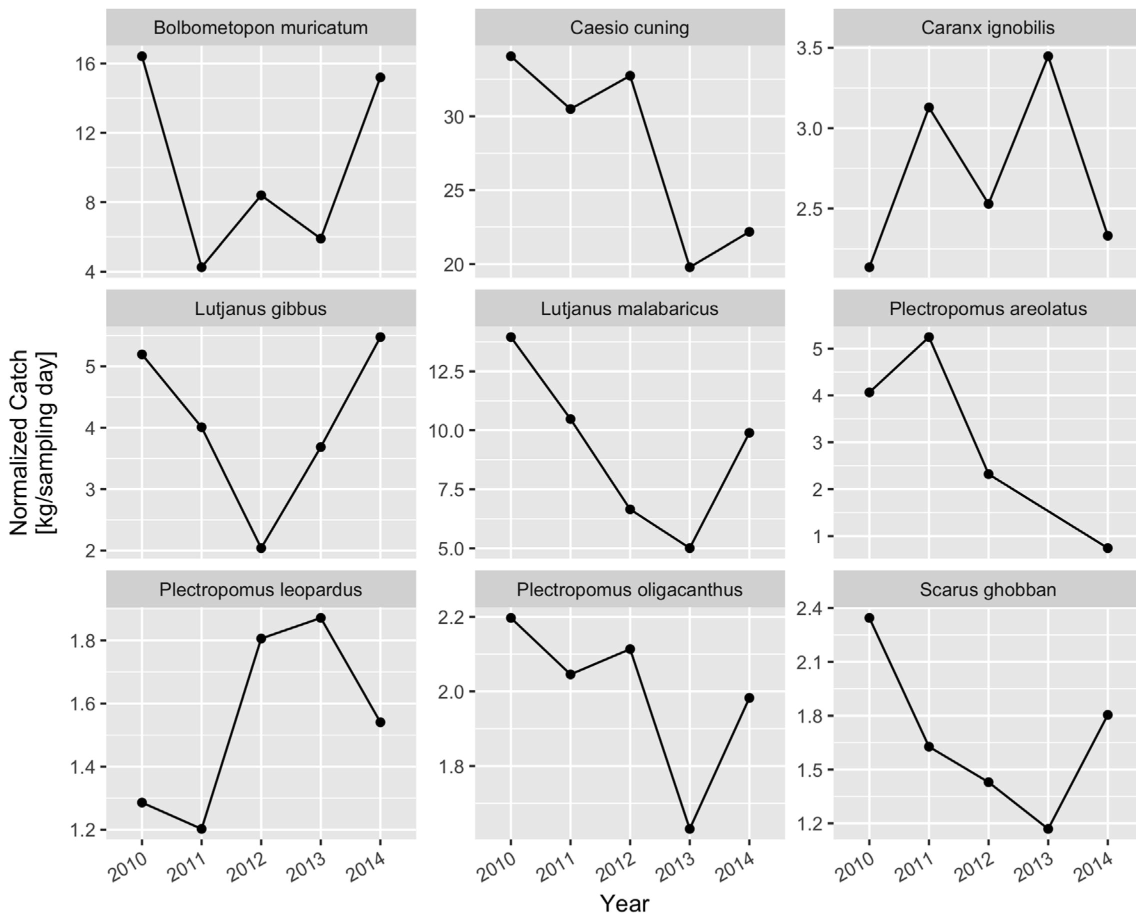

Fig. A2. Normalized catch (in terms of kg per sampling day) over time for each species. Data are aggregated across all management zones within KNP and across all gear types. Solid black lines are linearly interpolated between points to help observe trends.

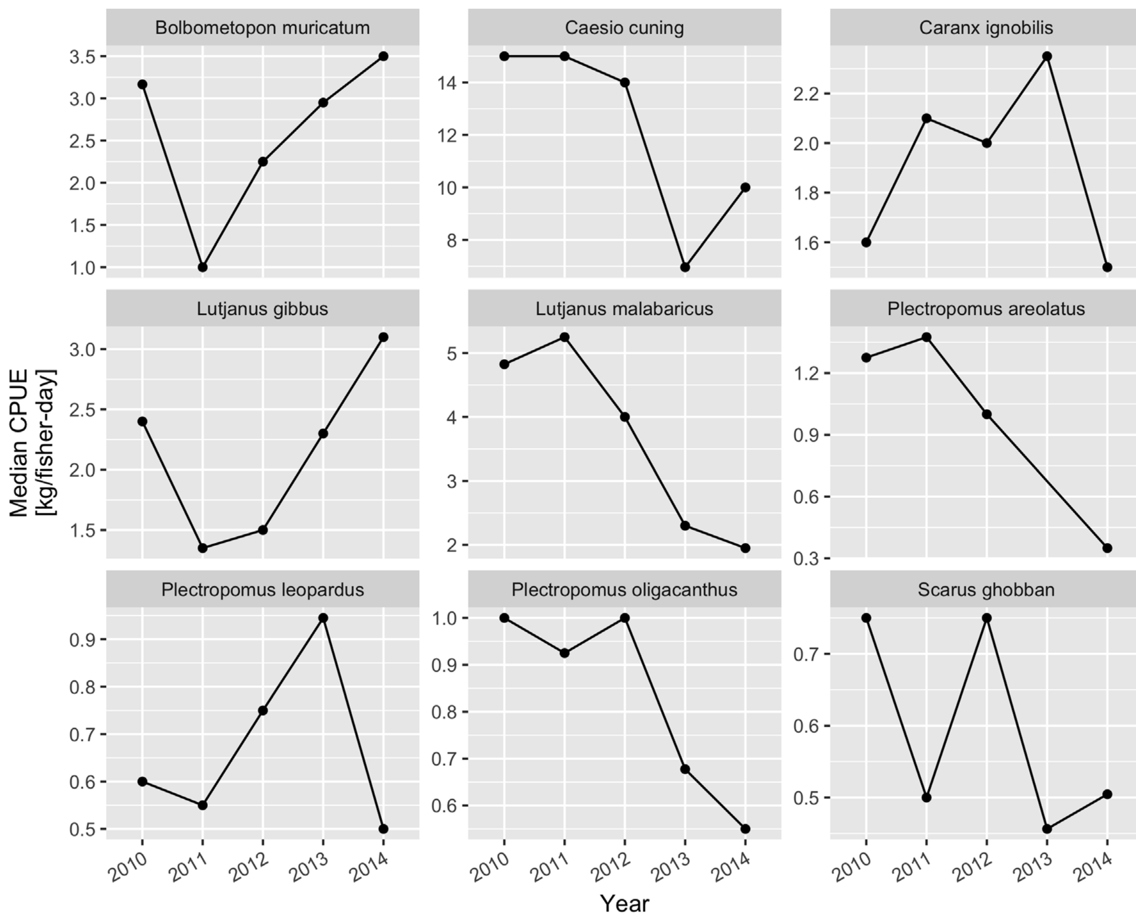

Fig. A3. Median catch-per-unit-effort (CPUE) (in terms of kg per fisher-day) over time for each species. Data are aggregated across all management zones within KNP and across all gear types. Solid black lines are linearly interpolated between points to help observe trends.

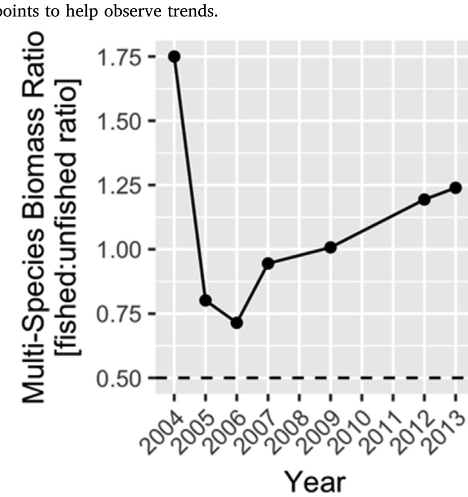

Fig. A4. Multi-species fished:unfished biomass ratio over time (aggregated across all observed species). A horizontal dashed line is shown at the TRP of 0.5. Solid black lines are linearly interpolated between points to help observe trends.

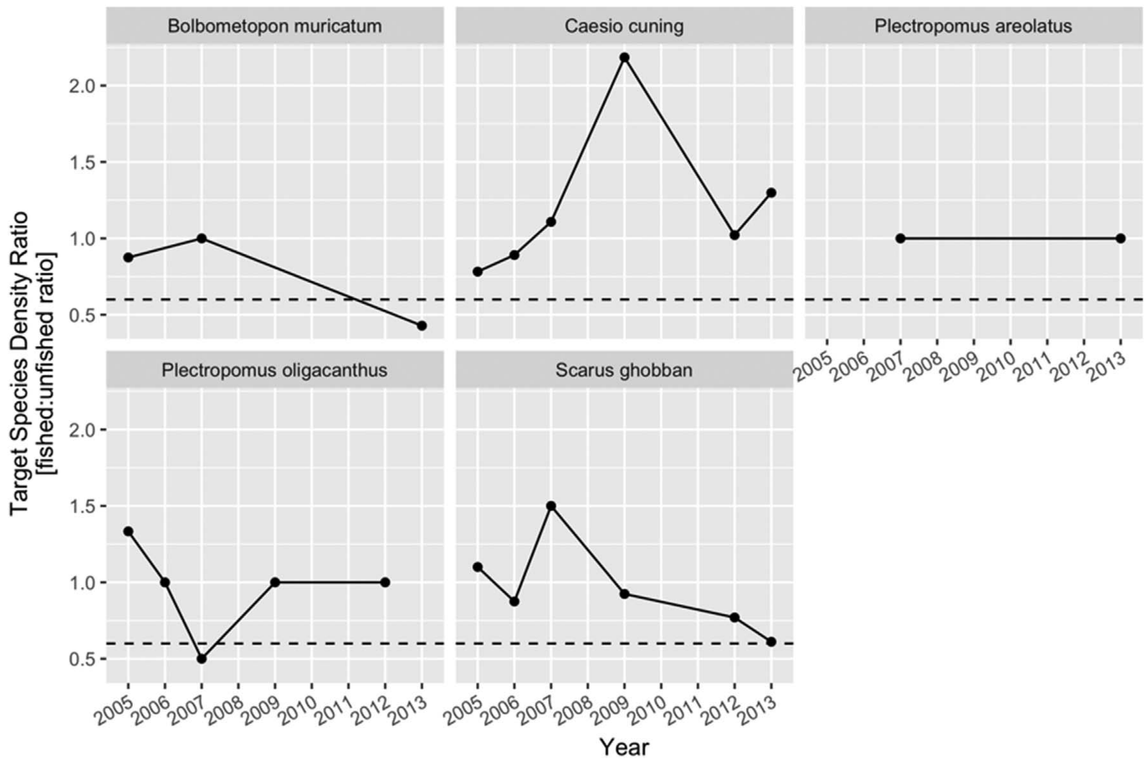

Fig. A5. Target species fished:unfished density ratio over time. A horizontal dashed line is shown at the TRP of 0.6. Solid black lines are linearly interpolated between points. Solid black lines are linearly interpolated between points to help observe trends.

Table A1
Target species life history information for KNP. Parameters included are von Bertalanffy growth parameters (V.B L_{inf}, V.B k, and V.B. t_0), instantaneous natural mortality (M), length-weight relationship parameters (a and b), lengths at 50% and 95% maturity (m_{50} and m_{95}), and maximum age (Max Age).

Scientific name	V.B. L_{inf}	V.B. k	V.B. t_0	M	a	b	m_{50}	m_{50}	Max Age
Units	cm	–	years	–	g and cm	g and cm	cm	cm	years
Bolbometopon muricatum	157.8 (Couture and Chauvet, 1994)	0.063 (Couture and Chauvet, 1994)	−0.470 (Couture and Chauvet, 1994)	0.236 (Randall et al., 1990)	0.0131 (Froese et al., 2014)	3.050 (Froese et al., 2014)	53.5 (Hamilton et al., 2007)	61.0 (Hamilton et al., 2007; Stern-Pirlot, 2006)	40.0 (Hamilton et al., 2007)
Caesio cuning	62.2 (Carpenter, 1987)	0.320 (Carpenter, 1987)	−0.420 (Carpenter, 1987)	0.892 (Carpenter, 1987)	0.0208 (Longenecker et al., 2014)	3.0322 (Longenecker et al., 2014)	13.95 (Longenecker et al., 2014)	15.9 (Longenecker et al., 2014; Stern-Pirlot, 2006)	9.0 (Carpenter, 1987)
Caranx ignobilis	184.0 (Abdussamad et al., 2008)	0.690 (Abdussamad et al., 2008)	−0.024 (Abdussamad et al., 2008)	0.223 (Paxton et al., 1989)	0.0202 (Pauly et al., 1996)	3.000 (Pauly et al., 1996)	54 (Williams, 1965)	61.56 (Williams, 1965; Stern-Pirlot, 2006)	26.3 (Paxton et al., 1989)
Lutjanus gibbus	44.9 (Martinez-Andrade, 2003)	0.32 (Martinez-Andrade, 2003)	−0.526 (Martinez-Andrade, 2003)	0.82 (Martinez-Andrade, 2003)	0.0210 (Kulbicki et al., 1993)	2.996 (Kulbicki et al., 1993)	25.4 (Martinez-Andrade, 2003)	28.96 (Martinez-Andrade, 2003; Stern-Pirlot, 2006)	10.8 (Martinez-Andrade, 2003)
Lutjanus malabaricus	84.3 (Martinez-Andrade, 2003)	0.226 (Martinez-Andrade, 2003)	−0.49 (Martinez-Andrade, 2003)	0.4 (Martinez-Andrade, 2003)	0.0199 (Newman, 2002)	2.928 (Newman, 2002)	42 (Martinez-Andrade, 2003)	47.88 (Martinez-Andrade, 2003; Stern-Pirlot, 2006)	15.1 (Martinez-Andrade, 2003)
Plectropomus areolatus	76.4 (Williams et al., 2008)	0.090 (Williams et al., 2008)	−5.870 (Williams et al., 2008)	0.250 (Rhodes et al., 2013)	0.0100 (Williams et al., 2008)	3.270 (Williams et al., 2008)	36.6 (Rhodes et al., 2013)	41.7 (Rhodes et al., 2013;	12.0 (Rhodes et al., 2013)

								Stern-Pirlot, 2006)	
Plectropomus leopardus	52.2 (Ferreira, 1994)	0.354 (Ferreira, 1994)	−0.766 (Ferreira, 1994)	0.214 (Ferreira, 1994)	0.0118 (Kulbicki et al., 1993)	3.060 (Kulbicki et al., 1993)	34.0 (Ferreira, 1994)	38.8 (Ferreira, 1994; Stern-Pirlot, 2006)	14.0 (Ferreira, 1994)
Plectropomus oligacanthus	77.5 (Heemstra, 1993)	0.150 (Heemstra, 1993)	−0.880 (Heemstra, 1993)	0.157 (Heemstra, 1993)	0.0132 ("Database of IGFA angling records until 2001," n.d.)	3.000 ("Database of IGFA angling records until 2001," n.d.)	41.5 (Heemstra, 1993)	47.3 (Heemstra, 1993; Stern-Pirlot, 2006)	22.0 ("Database of IGFA angling records until 2001," n.d.)
Scarus ghobban	42.9 (Sabetian, 2010)	0.650 (Sabetian, 2010)	−0.070 (Sabetian, 2010)	0.821 (Parenti and Randall, 2000)	0.0233 (Murty, 2002)	2.919 (Murty, 2002)	21.05 (Sabetian, 2010), [57]	24 (Sabetian, 2010; Stern-Pirlot, 2006)	6 (Sabetian, 2010)

References

Abdussamad, E.M., Kasim, H.M., Balasubramanian, T.S., 2008. Distribution, biology and behaviour of the giant trevally, Caranx ignobilis - a candidate species for mariculture. Bengladesh J. Fish. Res. 12 (1), 89–94.

Aswani, Shankar, Hamilton, R.J., 2004. Integrating indigenous ecological knowledge and customary sea tenure with marine and social science for conservation of bumphead parrotfish (Bolbometopon muricatum) in the Roviana Lagoon, Solomon Islands. Environ. Conserv. 31, 69–83. http://dx.doi.org/10.1017/S037689290400116X.

Ault, J., Smith, S., Bohnsack, J., 2005. Evaluation of average length as an estimator of exploitation status for the Florida coral-reef fish community. ICES J. Mar. Sci. 62, 417–423.

Authority, K.N.P., 2016. The 2015 Statistics of Karimunjawa National Park.

Babcock, E.A., MacCall, A.D., 2011. How useful is the ratio of fish density outside versus inside no-take marine reserves as a metric for fishery management control rules? Can. J. Fish. Aquat. Sci. 68, 343–359. http://dx.doi.org/10.1139/F10-146.

Babcock, E.A., Coleman, R., Karnauskas, M., Gibson, J., 2013. The influence of uncertainty in life history parameters on the estimation of status using low-data assessment methods. In: Proc. 66th Gulf Caribb. Fish. Inst. Novemb. 4 – 8, 2013 Corpus Christi, Texas USA, pp. 78–79.

Battista, W., Karr, K., Sarto, N., Fujita, R., 2016. Comprehensive Assessment of Risk to Ecosystems (CARE): a cumulative ecosystem risk assessment tool. Fish. Res. http://dx.doi.org/10.1016/j.fishres.2016.09.017.

Beddington, J.R., Agnew, D.J., Clark, C.W., 2007. Current problems in the management of marine fisheries. Science 316, 1713–1716. http://dx.doi.org/10.1126/science.1137362.

Caddy, J.F., 2015. The traffic light procedure for decision- making: its rapid extension from fisheries to other sectors of the economy. Glob. J. Sci. Front. Res. 15 (1), 11–39.

Caddy, J.F., 1999. Deciding on precautionary management measures for a stock based on a suit of limit reference points (LRPs) as a basis for a multi-LRP harvest law. NAFO Sci. Counc. Stud. 32, 55–68.

Caddy, J.F., Mahon, R., 1998. A Short Review of Precautionary Reference Points and Some Proposals or their Use in Data Poor Situations. FAO Tech. Pap. .

Campbell, S.J., Hoey, A.S., Maynard, J., Kartawijaya, T., Cinner, J., Graham, N.A.J., Baird, A.H., 2012. Weak compliance undermines the success of No-Take zones in a large government-controlled marine protected area. PLoS One 7, e50074. http://dx.doi.org/10.1371/journal.pone.0050074.

Campbell, S.J., Mukminin, A., Kartawijaya, T., Huchery, C., Cinner, J.E., 2014. Changes in a coral reef fishery along a gradient of fishing pressure in an Indonesian marine protected area. Aquat. Conserv. Mar. Freshw. Ecosyst. 24, 92–103. http://dx.doi.org/10.1002/aqc.2359.

Carpenter, K.E., 1987. Revision of the Indo-Pacific fish family Caesionidae (Lutjanoidea); with descriptions of five new species. [WWW Document]. Indo. Pac. Fish.(15). http://www.reefbase.org/resource_center/publication/pub_9448.aspx, Accessed date: 2 April 2016.

Carruthers, T.R., 2014. Data-limited Fisheries Toolkit (v. 1.3.4).

Carruthers, T.R., Punt, A.E., Walters, C.J., MacCall, A., McAllister, M.K., Dick, E.J., Cope, J., 2014. Evaluating methods for setting catch limits in data-limited fisheries. Fish. Res. http://dx.doi.org/10.1016/j.fishres.2013.12.014.

Chang, Winston, Cheng, Joe, Allaire, J.J., Xie, Yihui, McPherson, J., 2017. Shiny: Web Application Framework for R.

Cope, J.M., Punt, A.E., 2009. Length-based reference points for data-limited situations: applications and restrictions. Mar. Coast. Fish. 1, 169–186. http://dx.doi.org/10.1577/C08-025.1.

Costello, C., Ovando, D., Hilborn, R., Gaines, S.D., Deschenes, O., Lester, S.E., 2012. Status and solutions for the world's unassessed fisheries. Science 338 (80), 517–520.

Couture, E., Chauvet, C., 1994. Growth of the Green Humphead Parrotfish (Bolbometopon Muricatum) and its Exploitation in New Caledonia.

Dabbish, L., Stuart, C., Tsay, J., Herbsleb, J., 2012. Social coding in GitHub. In: Proceedings of the ACM 2012 Conference on Computer Supported Cooperative Work - CSCW '12. ACM Press, New York, New York, USA, pp. 1277. http://dx.doi.org/10.1145/2145204.2145396.

Database of IGFA angling records until 2001 [WWW Document], n.d. URL http://www.fishbase.ca/Biblio/BiblioSummary.php?id = 40637&speccode = 7319&syncode = 26483 (accessed 2.5.2016).

Deguit, E.T., Smith, R.P., Jatulan, W.P., White, A.T., 2004. Participatory Coastal Resource Assessment. Cebu City, Philippines. .

Dowling, N.A., Wilson, J.R., Rudd, M.B., Babcock, E.A., Caillaux, M., Cope, J., Dougherty, D., Fujita, R., Gedamke, T., Gleason, M., Gutiérrez, N.L., Hordyk, A., Maina, G.W., Mous, P., Ovando, D., Parma, A.M., Prince, J., Revenga, C., Rude, J., Szuwalski, C., Valencia, S., Victor, S., 2016. FishPath: a decision support system for assessing and managing data- and capacity-limited fisheries. In: Assessing and Managing Data-limited Fish Stocks, pp. 59–95. http://dx.doi.org/10.4027/amdlfs.2016.03.

Ehrhardt, N.M., Ault, J.S., 1992. Analysis of two length-based mortality models applied to bounded catch length frequencies. Trans. Am. Fish. Soc. 121, 115–122.

Environmental Defense Fund, 2013. FISHE: Framework for Integrated Stock and Habitat Evaluation. [WWW Document].

Evans, L., Cherrett, N., Pemsl, D., 2011. Assessing the impact of fisheries co-management interventions in developing countries: a meta-analysis. J. Environ. Manage. 92, 1938–1949. http://dx.doi.org/10.1016/j.jenvman.2011.03.010.

FAO, 2017. Strategy for Improving Information on Status and Trends of Capture Fisheries. [WWW Document]. FAO Fish. Aquac. Dep. http://www.fao.org/fishery/fishcode-stf/activities/ssf/en, Accessed date: 5 January 2017.

FAO Fisheries & Aquaculture Department, 2016. EAFnet. [WWW Document].

Ferreira, B.P., 1994. Age validation and estimation of growth rate of the coral trout, Plectropomus leopardus, (Lacepede 1802) from Lizard Island. North. Gt. Barrier Reef. 92, 46–57.

Floeter, S.R., Behrens, M.D., Ferreira, C.E.L., Paddack, M.J., Horn, M.H., 2005. Geographical gradients of marine herbivorous fishes: patterns and processes. Mar. Biol. 147, 1435–1447. http://dx.doi.org/10.1007/s00227-005-0027-0.

Froese, R., 2004. Keep it simple: three indicators to deal with overfishing. Ghoti papers Ghoti aims to serve as a forum for stimulating and pertinent ideas. Ghoti publishes succinct commentary and opinion that addresses important areas in fish and fisheries science. Ghoti. Fish. Fish. 5, 86–91. http://dx.doi.org/10.1111/j.1467-2979.2004.00144.x.

Froese, R., Pauly, D., 2017. FishBase. [WWW Document]. www.fishbase.org, Accessed date: 26 April 2017.

Froese, R., Thorson, J.T., Reyes, R.B., 2014. A Bayesian approach for estimating length-weight relationships in fishes. J. Appl. Ichthyol. 30, 78–85. http://dx.doi.org/10.1111/jai.12299.

Fujita, R., Thornhill, D.J., Karr, K., Cooper, C.H., Dee, L.E., 2014. Assessing and managing data-limited ornamental fisheries in coral reefs. Fish. Fish. 15, 661–675.

GitHub [WWW Document], 2017. URL https://github.com/(accessed 6.1.17).

Gust, N., Choat, J., Ackerman, J., 2002. Demographic plasticity in tropical reef fishes. Mar. Biol. 140, 1039–1051. http://dx.doi.org/10.1007/s00227-001-0773-6.

Hamilton, R.J., Adams, S., Choat, J.H., 2007. Sexual development and reproductive demography of the green humphead parrotfish (Bolbometopon muricatum) in the Solomon Islands. Coral Reefs 27, 153–163. http://dx.doi.org/10.1007/s00338-007-0304-0.

Harford, W.J., Gedamke, T., Babcock, E.A., Carcamo, R., McDonald, G., Wilson, J., 2016. Management strategy evaluation of a multi-indicator adaptive framework for data-limited fisheries management. Bull. Mar. Sci. http://dx.doi.org/10.5343/bms.2016.1025.

Heemstra, P.C., J.E.R, 1993. [WWW Document]. FAO Species Catalogue. Vol. 16. Groupers of the World (Family Serranidae, Subfamily Epinephelinae). An Annotated and Illustrated Catalogue of the Grouper, Rockcod, Hind, Coral Grouper and Lyretail Species Known to Date, vol. 125(16) Rome FAO. FAO Fish. Synop. http://www.fishbase.org/references/FBRefSummary.php?ID = 5222, Accessed date: 5 February 2016.

Hoenig, J.M., Then, A.Y.-H., Babcock, E.A., Hall, N.G., Hewitt, D.A., Hesp, S.A., 2016. The logic of comparative life history studies for estimating key parameters, with a focus

on natural mortality rate. ICES J. Mar. Sci. J. du Cons. 73, 2453–2467. http://dx.doi.org/10.1093/icesjms/fsw089.
Holt, B.G., Rioja-Nieto, R., Aaron MacNeil, M., Lupton, J., Rahbek, C., 2013. Comparing diversity data collected using a protocol designed for volunteers with results from a professional alternative. Methods Ecol. Evol. 4, 383–392. http://dx.doi.org/10.1111/2041-210X.12031.
Honey, K.T., Moxley, J.H., Fujita, R.M., 2010. From rags to fishes: data-poor methods for fishery managers. Manag. Data Poor Fish. Case Stud. Model. Solut. 1, 159–184.
Hordyk, A., 2017. LBSPR: Length-based Spawning Potential Ratio.
Hordyk, A., Ono, K., Valencia, S., Loneragan, N., Prince, J., 2014a. A novel length-based empirical estimation method of spawning potential ratio (SPR), and tests of its performance, for small-scale, data-poor fisheries. In: ICES Journal of Marine Science. Oxford University Press, pp. 217–231.
Jepara Regency in Figures - Statistics of Jepara Regency, 2015.
Johannes, R., 1998. The case for data-less marine resource management: examples from tropical nearshore finfisheries. Trends Ecol. Evol. 13, 243–246. http://dx.doi.org/10.1016/S0169-5347(98)01384-6.
Karr, K.A., Fujita, R., Halpern, B.S., Kappel, C.V., Crowder, L., Selkoe, K.A., Alcolado, P.M., Rader, D., 2015. Thresholds in Caribbean coral reefs: implications for ecosystem-based fishery management. J. Appl. Ecol. 52, 402–412. http://dx.doi.org/10.1111/1365-2664.12388.
Kay, Matthew C., Wilson, J.R., 2012. Spatially explicit mortality of California spiny lobster (Panulirus interruptus) across a marine reserve network. [WWW Document]. Environ. Conserv. 39. http://journals.cambridge.org/action/displayFulltext?type=1&fid=8676534&jid=ENC&volumeId=39&issueId=03&aid=8676532&bodyId=&membershipNumber=&societyETOCSession=, Accessed date: 3 February 2016.
Kulbicki, M., Mou Tham, G., Thollot, P., Wantiez, L., 1993. Length-weight Relationships of Fish from the Lagoon of New Caledonia. Naga, ICLARM Q.
Little, L.R., et al., 2011. Development and evaluation of a cpue-based harvest control rule for the south eastern scalefish and shark fishery of Australia. ICES J. Mar. Sci. 68, 1699–1705.
Liu, O.R., Thomas, L.R., Clemence, M., Fujita, R., Kritzer, J.P., McDonald, G., Szuwalski, C., 2016. An evaluation of harvest control methods for fishery management. Rev. Fish. Sci. Aquac. 24 (3), 244–263.
Longenecker, K., Langston, R., Bolick, H., Kondio, U., 2014. Rapid reproductive analysis and length–weight relation for red-bellied fusilier, Caesio cuning, and longfin emperor, Lethrinus erythropterus (Actinopterygii: perciformes: Caesionidae and Lethrinidae) from a remote village in Papua New Guinea. Acta Ichthyol. Piscat. 44, 75–84. http://dx.doi.org/10.3750/AIP2014.44.1.10.
Mahon, R., 1997. Does fisheries science serve the needs of managers of small stocks in developing countries. Can. J. Fish. Aquat. Sci. 54, 2207–2213. http://dx.doi.org/10.1139/f97-112.
Martinez-Andrade, F., 2003. A Comparison of Life Histories and Ecological Aspects Among Snappers (Pisces:Lutjanidae).
McCay, B.J., Micheli, F., Ponce-Díaz, G., Murray, G., Shester, G., Ramirez-Sanchez, S., Weisman, W., 2014. Cooperatives, concessions, and co-management on the Pacific coast of Mexico. Mar. Policy 44, 49–59. http://dx.doi.org/10.1016/j.marpol.2013.08.001.
McClanahan, T.R., Graham, N.A.J., MacNeil, M.A., Muthiga, N.A., Cinner, J.E., Bruggemann, J.H., Wilson, S.K., 2011. Critical thresholds and tangible targets for ecosystem-based management of coral reef fisheries. Proc. Natl. Acad. Sci. U. S. A. 108, 17230–17233. http://dx.doi.org/10.1073/pnas.1106861108.
McDonald, G., Harford, B., Arrivillaga, A., Babcock, E.A., Carcamo, R., Foley, J., Fujita, R., Gedamke, T., Gibson, J., Karr, K., Robinson, J., Wilson, J., 2017. An indicator-based adaptive management framework and its development for data-limited fisheries in Belize. Mar. Policy 76, 28–37. http://dx.doi.org/10.1016/j.marpol.2016.11.027.
McGilliard, C.R., Hilborn, R., MacCall, A., Punt, A.E., Field, J.C., 2010. Can information from marine protected areas be used to inform control-rule-based management of small-scale, data-poor stocks? ICES J. Mar. Sci. 68, 201–211.
Mildenberger, T.K., Taylor, M.H., Wolff, M., 2017. TropFishR: Tropical Fisheries Analysis with R.
Murty, V.S., 2002. Marine ornamental Fish Resources of Lakshadweep. C. Spec. Publ.
Newman, D., Carruthers, T., MacCall, A., Porch, C., Suatoni, L., 2014. Improving the Science and Management of Data-limited Fisheries: an Evaluation of Current Methods and Recommended Approaches. New York, New York.
Newman, S.J., 2002. Growth rate, age determination, natural mortality and production potential of the scarlet seaperch, Lutjanus malabaricus Schneider 1801, off the Pilbara coast of north-western Australia. Fish. Res. 58, 215–225. http://dx.doi.org/10.1016/S0165-7836(01)00367-8.
NOAA, 2014. NOAA Fisheries Toolbox.
Oyanedel, R., Macy-Humberstone, J., Shattenkirk, K., Rodriguez Van-Dyck, S., Joye Moyer, K., Poon, S., McDonald, G., Ravelo-Salazar, C., Mancao, R., Clemence, M., Costello, Christopher, 2016. A decision support tool for designing TURF-reserves. Bull. Mar. Sci. http://dx.doi.org/10.5343/bms.2015.1095.
Parenti, Paolo, Randall, J.E., 2000. An Annotated Checklist of the Species of the Labroid Fish Families Labridae and Scaridae. [WWW Document]. chthyological Bull. J.L.B. Smith Inst. Ichthyol. No. 68. http://www.bioline.org.br/request?fb00001, Accessed date: 4 February 2016.
Patrick, Wesley S., Spencer, Paul, Link, Jason, Cope, Jason, Field, John, Kobayashi, Donald, Lawson, Peter, Gedamke, Todd, Cortés, Enric, Ormseth, Olav, Bigelow, Keith, Overholtz, W., 2010. Using productivity and susceptibility indices to assess the vulnerability of United States fish stocks to overfishing. Fish. Bull. 108, 305–322.
Pauly, D., Cabanban, A., Torres Jr., F.S.B., 1996. Fishery biology of 40 trawl-caught teleosts of western Indonesia. [WWW Document]. Baseline Stud. Biodivers. Fish. Resour. West. Indones. ICLARM Stud. Rev. 23. http://www.fishbase.org/references/FBRefSummary.php?id=12260&speccode=491&lang=french, Accessed date: 4 February 2016.
Paxton, J.R., Hoese, D.F., Allen, G.R., Hanley, J.E., 1989. [WWW Document]. Zoological Catalogue of Australia. Pisces. Petromyzontidae to Carangidae, vol. 7 Australian Government Publishing Service, Canberra URL. http://www.reefbase.org/resource_center/publication/pub_6821.aspx, Accessed date: 2 April 2016.
Petitgas, P., 2009. The CUSUM out-of-control table to monitor changes in fish stock status using many indicators. Aquat. Living Resour. 22, 201–206. http://dx.doi.org/10.1051/alr/2009021.
Pitcher, T.J., Preikshot, D., 2001. Rapfish: a rapid appraisal technique to evaluate the sustainability status of fisheries. Fish. Res. 49, 255–270. http://dx.doi.org/10.1016/S0165-7836(00)00205-8.
Prince, J., Victor, S., Kloulchad, V., Hordyk, A., 2015. Length based SPR assessment of eleven Indo-Pacific coral reef fish populations in Palau. Fish. Res. 171, 42–58. http://dx.doi.org/10.1016/j.fishres.2015.06.008.
Prince, J.D., Dowling, N.A., Davies, C.R., Campbell, R.A., Kolody, D.S., 2011. A simple cost-effective and scale-less empirical approach to harvest strategies. ICES J. Mar. Sci. 68, 947–960. http://dx.doi.org/10.1093/icesjms/fsr029.
Randall, J.E., Allen, G.R., Steene, R., 1990. Fishes of the Great Barrier Reef and Coral Sea. [WWW Document]. University of Hawaii Press, Honolulu, Hawaii.
Rhodes, K.L., Taylor, B.M., Wichilmel, C.B., Joseph, E., Hamilton, R.J., Almany, G.R., 2013. Reproductive biology of squaretail coralgrouper Plectropomus areolatus using age-based techniques. J. Fish. Biol. 82, 1333–1350. http://dx.doi.org/10.1111/jfb.12076.
Sabetian, A., 2010. Parrotfish Fisheries and Population Dynamics: a Case-study from Solomon Islands.
Sale, P.F., Sharp, B.J., 1983. Correction for bias in visual transect censuses of coral reef fishes. Coral Reefs 2, 37–42. http://dx.doi.org/10.1007/BF00304730.
Sparr, Per, Venema, S.C., 1998. Introduction to Tropical Fish Stock Assessment - Part 1: Manual. (French version not published) [WWW Document]. FAO Fish. Tech. Pap. 306. http://www.fao.org/docrep/w5449e/w5449e00.htm, Accessed date: 3 February 2016.
St John, J., Russ, G., Gladstone, W., 1990. Accuracy and bias of visual estimates of numbers, size structure and biomass of a coral reef fish. Mar. Ecol. Prog. Ser. 64, 253–262.
Stern-Pirlot, A., 2006. Maturity Tool Info. [WWW Document]. INCOFISH Work, 7.2 Lima, Peru. http://www.incofish.org/workpackages/wp7/Downloads/MaturityToolInfo.pdf, Accessed date: 8 February 2016.
Team, R.C., 2013. R: a Language and Environment for Statistical Computing.
Thresher, R.E., Gunn, J.S., 1986. Comparative analysis of visual census techniques for highly mobile, reef-associated piscivores (Carangidae). Environ. Biol. Fishes 17, 93–116. http://dx.doi.org/10.1007/BF00001740.
Wamukota, A.W., Cinner, J.E., McClanahan, T.R., 2012. Co-management of coral reef fisheries: a critical evaluation of the literature. Mar. Policy 36, 481–488. http://dx.doi.org/10.1016/j.marpol.2011.09.001.
Wayte, S.E., Klaer, N.L., 2010. An effective harvest strategy using improved catch-curves. Fish. Res. 106, 310–320.
Williams, A.J., Currey, L.M., Begg, G.A., Murchie, C.D., Ballagh, A.C., 2008. Population biology of coral trout species in eastern Torres Strait: implications for fishery management. Cont. Shelf Res. 28, 2129–2142. http://dx.doi.org/10.1016/j.csr.2008.03.021.
Williams, F., 1965. Further notes on the biology of East African pelagic fishes of the families Carangidae and Sphyraenidae.
Willman, R., Kelleher, K., Arnason, R., Franz, N., 2009. The Sunken Billions: the Economic Justification for Fisheries Reform. Agric. Rural Dev. Ser.
Wolkovich, E.M., Regetz, J., O'Connor, M.I., 2012. Advances in global change research require open science by individual researchers. Glob. Chang. Biol. 18, 2102–2110. http://dx.doi.org/10.1111/j.1365-2486.2012.02693.x.
Xie, Y., 2016. Bookdown: Authoring Books and Technical Documents with R Markdown.