ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/345943958

Emerging Science and Technology to Improve Monitoring and Assessments of Fish Spawning Aggregations Report from the 2019 Gulf and Caribbean Fisheries Institute Workshop

Technical Report · October 2020

CITATIONS
0

READS
13

37 authors, including:

Michelle T. Schärer
University of Puerto Rico at Mayagüez
54 PUBLICATIONS **645** CITATIONS

SEE PROFILE

Kelly Kingon
University of Trinidad and Tobago (UTT)
18 PUBLICATIONS **83** CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:

Project Marine Acoustics View project

Project Social Ecological Systems View project

All content following this page was uploaded by Kelly Kingon on 16 November 2020.

The user has requested enhancement of the downloaded file.

Emerging Science and Technology for Monitoring and Assessment of Fish Spawning Aggregations

NOAA Technical Memorandum NMFS-F/SPO-207
October 2020

Cover photo credit: Cover photographs of twin spot red snapper (*Lutjanus bohar*) spawning aggregations in Palau were taken are used by explicit permission granted by the photographer, Mr. Richard Barnden.

Emerging Science and Technology to Improve Monitoring and Assessments of Fish Spawning Aggregations

Report from the 2019 Gulf and Caribbean Fisheries Institute Workshop

J. Christopher Taylor[1], Mandy Karnauskas[2], Laurent Cherubin[3], Michelle Schärer-Umpierre[4], William L. Michaels[5], Ryan Caillouet[6], Matthew Campbell[6], David Demer[7], Brad Erisman[8], Stuart Fulton[9], Scott Heppell[10], William Heyman[11], Kelly Kingon[12], Danielle Morley[13], Richard Nemeth[14] Joanna Pitt[15], Timothy Rowell[16], and Brice Semmens[17]

[1]NOAA National Center for Coastal Ocean Science, Beaufort, NC; [2]NOAA Southeast Fisheries Science Center, Miami, FL; [3]Florida Atlantic University, Boca Raton, FL; [4]HJR Reefscaping, Boquerón, PR; [5]NOAA Fisheries Office of Science and Technology, Silver Spring, MD; [6]NOAA Southeast Fisheries Science Center, Pascagoula, MS; [7]NOAA Southwest Fisheries Science Center, San Diego, CA; [8]University of Texas Marine Science Institute, Port Aransas, TX; [9]Comunidad y Biodiversidad A.C., Cancun, Mexico; [10]Oregon State University, Corvallis, OR; [11]LGL Ecological Research Associates, Inc, Bryan, TX; [12]University of Trinidad and Tobago; [13]Florida Fisheries and Wildlife Research Institute, Marathon, FL; [14]University of the Virgin Islands; [15]Bermuda Department of Environment and Natural Resources; [16]NOAA Northeast Fisheries Science Center, Woods Hole, MA; [17]Scripps Institute of Oceanography, San Diego, CA

October 2020

NOAA Technical Memorandum NMFS-F/SPO-207

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

National Oceanic and Atmospheric Administration
Neil A. Jacobs, PhD
Acting Under Secretary for Oceans and Atmosphere

National Marine Fisheries Service
Christopher W. Oliver
Assistant Administrator for Fisheries

Recommended Citation:

Taylor, J.C., M. Karnauskas, L. Cherubin, M. Schärer-Umpierre, W.L. Michaels, R. Caillouet, M. Campbell, D. Demer, B. Erisman, S. Fulton, S.A. Heppell, W. Heyman, K. Kingon, D. Morley, R. Nemeth, J. Pitt, T. Rowell, and B. Semmens. 2020. Emerging Science and Technology to Improve Monitoring and Assessments of Fish Spawning Aggregations. Report from the 2019 Gulf and Caribbean Fisheries Institute Workshop. NOAA Tech. Memo. NMFS-F/SPO-207, 74 p.

Available online at https://spo.nmfs.noaa.gov/tech-memos

The National Marine Fisheries Service (NMFS, or NOAA Fisheries) does not approve, recommend, or endorse any proprietary product or proprietary material mentioned in the publication. No reference shall be made to NMFS, or to this publication furnished by NMFS, in any advertising or sales promotion that would indicate or imply that NMFS approves, recommends, or endorses any proprietary product or proprietary material mentioned herein, or which has as its purpose an intent to cause directly or indirectly the advertised product to be used or purchased because of this NMFS publication.

Table of Contents

List of Figures

Acknowledgments

This symposium, workshop and resulting report was made possible through the Gulf and Caribbean Fisheries Institute (GCFI) Ocean Innovation Strategic Initiative grant supported by the National Oceanic Atmospheric Administration (NOAA). Robert Glazer (GCFI Executor Director) is acknowledged for the grant submission with the goal of improving scientific information using innovative technologies for the sustainability of living marine resources in the Gulf of Mexico and Caribbean regions. Financial support of this grant was provided by the NOAA Fisheries' Office of Science and Technology, in addition to the GCFI-NOAA partnership. Chris Taylor, Mandy Karnauskas, Laurent Cherubin, Michelle Sharer, and William Michaels are recognized for their efforts to organize and facilitate the workshop. The workshop participants provided a diverse and broad range of expertise and balanced perspectives that directly contributed to the success of the workshop.

Executive Summary

The Gulf and Caribbean Fisheries Institute (GCFI) and National Oceanic and Atmospheric Administration (NOAA) have sponsored a series of workshops to help improve data-limited assessments of fisheries in the Gulf and Caribbean region. This year's GCFI-NOAA Workshop titled "To Improve the Monitoring and Abundance Estimation of Fish Spawning Aggregations (FSAs) in the Gulf and Caribbean Region" was held in Punta Cana, Dominican Republic during November 2-3, 2019. The workshop brought together the expertise and diverse perspectives of 51 participants from 12 countries to address research priorities and identify knowledge gaps to improve the scientific information of FSAs for fisheries management. A pre-workshop survey guided the framework of the workshop, and survey responses highlighted the interest and training needs for the application of new technologies and methods to enhance the monitoring of FSAs. The workshop focused on two primary goals: (1) Enhance the scientific capacity within the GCFI community and establish best practices in conducting research and monitoring of reef fish spawning aggregations (FSA) using integrated technologies, and (2) Evaluate the scientific data requirements for stock management (e.g., ensuring sustainable populations) and spatial management (e.g., conserving single or multi-species spawning aggregations) strategies for FSAs.

Workshop goals were achieved through a series of plenary discussions, break-out group exercises, and interactive case study problem solving sessions. Plenary presentations introduced workshop participants to emerging optical, acoustical, and remote sensing technologies that can be used to improve scientific information on FSAs. Two plenary case studies highlighted successes in long-term assessment and monitoring programs for FSAs. Breakout group discussions gave participants the opportunity to design a monitoring program for a hypothetical fishery, as well as provide advice for a number of real-world FSA management scenarios. Breakout sessions also established criteria for survey and monitoring designs for data needs to inform stock assessments and identified high priority actions that could help fill important information gaps to improve the conservation and management of FSAs.

Considerable discussion was focused on the need to address the information gaps associated with the spatial uncertainties in the assessment of FSAs. The size and extent of many FSAs are often only periodically assessed, leaving gaps in survey data for detecting trends and dynamics in FSAs that could be linked to management actions. Cost-effective tools and survey designs were discussed to better understand the spatio-temporal variation in FSAs, especially at a time of elevated environmental changes in response to climate change. There was also discussion on how to characterize FSA populations with limited resources, and to assess their potential recovery following implementation of adequate management practices. There was consensus that cost-effective technologies can improve FSA monitoring and biomass estimation, and data on length compositions and sex ratios would be most useful to enhance assessments of stock status and/or trends. More tagging and genetic studies are needed to understand how FSAs might represent status and trends of the population, particularly in terms of connectivity across geopolitical boundaries. Finally, concerns were raised during the workshop highlighting the need for new technologies that enhance managers' ability to monitor illegal fishing activity and increase the enforcement of protected FSAs.

Throughout the discussions to improve monitoring programs and scientific information for informative FSA assessments, specific attention was paid to the varying levels of funding and staffing resources available for fisheries management among the countries of the wider Caribbean region. Developing networks of collective expertise and collaborative studies

remains the more cost-effective strategy to build consensus on best practices and scientific capacity toward the goal of improved FSA assessments. It was broadly recognized that access to technology is often limited by budgets and expertise, and one potential way to address this would be to create an equipment pool that could be accessed by researchers in the region. The workshop participants have collectively provided recommendations built upon a rich history of recognition of and ongoing research on the significance of spawning aggregations in maintaining healthy coral reef ecosystems across the Gulf of Mexico and Caribbean regions. This GCFI-NOAA workshop and previous workshops provide the foundation to develop technical capacity throughout the region to optimize survey design and data collections with cost-effective technologies and methods for fisheries management decisions, and ultimately strengthen governance in the region for the sustainability of living marine resources.

Participants of the 2019 Gulf and Caribbean Fisheries Institute Workshop to Improve Monitoring and Abundance Estimation of Fish Spawning Aggregations held in Punta Cana, Dominican Republic during November 2-3, 2019.

I. Background - NOAA-GCFI Ocean Innovation Strategic Initiative

The US National Oceanic and Atmospheric Administration (NOAA) and Gulf and Caribbean Fisheries Institute (GCFI) have a long history of partnership to build capacity in fisheries management in the Caribbean region. Workshops held in concert with GCFI annual meetings have focused on data limitations and tradeoffs in fishery-dependent and -independent sampling (Cummings et al. 2017). Lack of fishery and habitat data impedes progress to manage fish stocks for sustainable use. A survey distributed to the GCFI community in 2016 inquired about priority needs and data gaps in fisheries, fish population dynamics, and coral reef habitat assessments. Hands-on workshops were identified as the best opportunity for training, developing best practices, introducing new tools, and fostering partnerships. Applying advanced technologies such as acoustics and underwater optical tools to coral reef fish ecosystems were identified as a need in the region. A series of three workshops were envisioned to address applications of integrating technologies to improve assessments of coral reef fish and habitats. The workshops are envisioned and designed to build upon each other; many of the participants are the same from year to year, and so the workshop series is intended to build diverse skillsets and capacity across the region to improve fishery management.

The 2017 NOAA-GCFI Workshop on Acoustic Technologies to Improve Reef Fish Ecosystem Surveys in Mérida, Mexico hosted over 50 participants from over 12 countries and kicked off with a brief field experiment where participants were exposed to a new portable and inexpensive echosounder manufactured by Simrad Kongsberg Maritime. Experts from NOAA and Universities in Mexico were on hand to answer questions about how acoustic technologies could be used to survey reef fishes and habitats. On the second day, participants contributed to a discussion that identified the key topic areas and data gaps in fisheries research and management that could be addressed with integrating acoustic technologies into surveys and assessments of fish stocks. Case studies highlighted recent efforts to improve assessments of coral reef fishes using acoustics to observe fish behavior, document fish aggregations, and estimate fish abundance using coupled acoustic and video technologies (Michaels et al. 2019a). An overview of survey and statistical sampling design was also provided. Participants contributed to a summary of best practices in selecting, deploying, and interpreting data from scientific echosounders and passive acoustic recorders.

Following the 2017 GCFI workshop, NOAA Fisheries and the Instituto Politécnico Nacional-CICIMAR hosted a field course in La Paz, Mexico and conducted a field training experiment on a small seamount in the Gulf of California in April 2018. A low-cost, efficient, acoustic-optical method was demonstrated by GCFI students. The method, which used echosounders and a conductivity-temperature-depth (CTD) probe deployed from a small boat, coupled with cameras cast on the CTD and deployed by SCUBA divers, was used to conduct a one-day survey of reef fishes and their seabed and oceanographic habitats, and estimate the abundances of two predominant species in a marine protected area (MPA) (Figure 1).

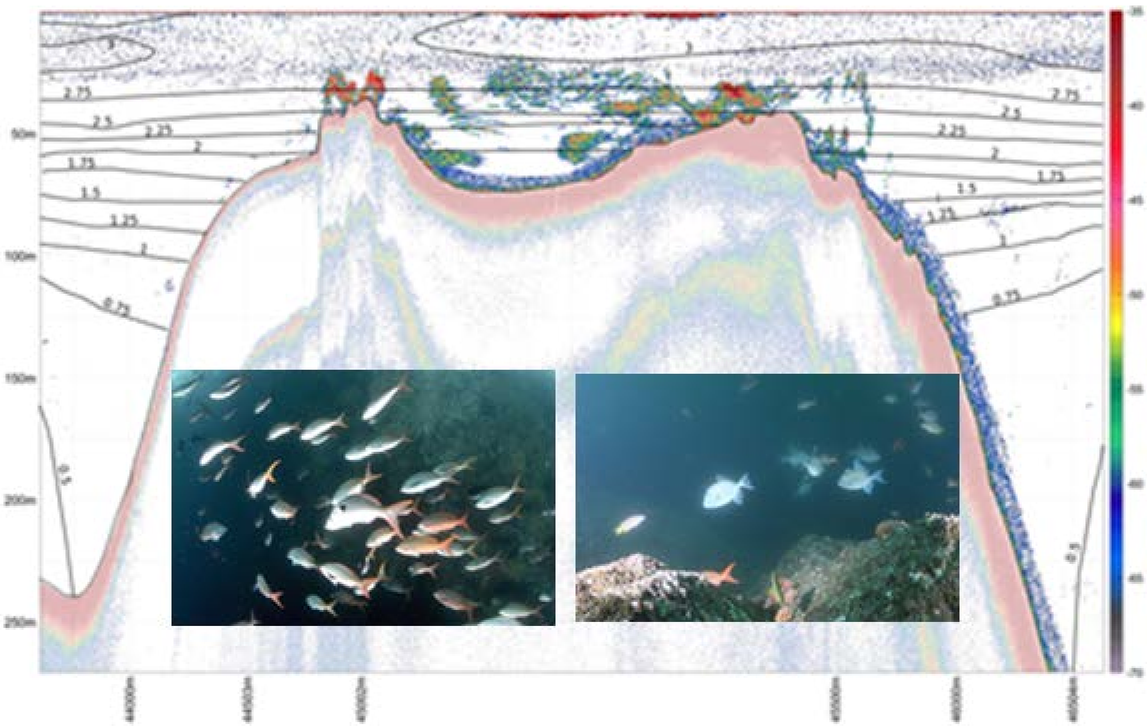


Figure 1. Echogram (blue to red indicated low to high acoustic backscatter) with dissolved oxygen levels, (contours) and underwater images of Pacific creolefish (left) and finescale triggerfish (right) at Espiritu Santo marine protected area (MPA) near La Paz, Mexico, during April 2018.

The 2018 the NOAA-GCFI Workshop on Integrated Optic-Acoustic Technology to Improve Reef Fish Surveys was held as part of GCFI 71 in San Andrés, Colombia. This workshop began with an intensive field experiment that included the deployment of a stationary autonomous split beam echosounder paired with stereo-video systems to collect simultaneous acoustic backscatter and fish species and size information on a fish community over a patchy coral reef habitat. The following day, participants at the workshop received training in analysis and interpretation of the acoustic and stereo optical data and developed summaries of observations made during the experiment including a comparison of target strength and fish size, patterns of fish abundance over time, swimming patterns of schooling fishes, and detection of fishes close to the seabed or in the “acoustic dead zone”. A summary report is in preparation.

Participants from both workshops and attendees at the 2018 GCFI conference were polled to identify the next workshop in the technology series. Improving assessments and abundance estimates of reef fish spawning aggregations (FSAs) was identified as a key management need with a number of important data gaps that could be informed by applications of emerging technologies. The 2019 GCFI was planned for November 4-8, 2019 in Punta Cana, Dominican Republic. A workshop steering committee planned a two-day workshop on November 2-3 November, 2019 preceding the GCFI conference.

II. Introduction to the 2019 GCFI FSA Workshop

The Gulf of Mexico and Caribbean regions host a diversity of fish species, many of which aggregate to spawn in concentrated space and time windows throughout the region. These fish spawning aggregations (FSAs) are the primary source of reproduction for many commercially important species in the region, providing an important source of income to commercial and recreational fisheries and protein for Caribbean island communities. The history of exploitation of the iconic Nassau grouper (*Epinephelus striatus*), for example, serves as a harbinger for the fate of other species that aggregate to spawn. In the 1960s, Nassau grouper was the most important commercially harvested finfish in the region, with harvests focused on the seasonal spawning aggregations occurring from November - January (Sadovy 1994). Olsen and La Place (1978) first enlightened the GCFI community regarding the biology and vulnerability of Nassau grouper FSAs as evidenced in the US Virgin Islands (Figure 2). Harvests remained high into the early 1980s, but the intensive harvest caused population reductions, and a majority of the known prominent FSAs ceased to form (Sadovy 1994). The population crash ultimately led to Nassau grouper being assessed in the IUCN Red List as 'critically endangered' throughout its range and as 'threatened' under the Endangered Species Act in the United States jurisdictions (NOAA 2016).

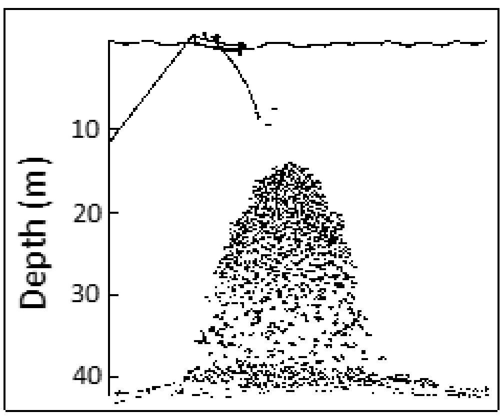


Figure 2. Nassau grouper spawning aggregation in the US Virgin Islands (adapted from Olsen and LaPlace, 1979)

Many other species of fish also aggregate to spawn, often at the same locations as Nassau grouper though with different seasonal patterns. These 'multi-species' spawning aggregation sites are recognized as critical for the survival of many of the region's most important commercially harvested species, yet harvest continues such that their plight may follow that of Nassau grouper. Recognizing the importance of this iconic species, several nations and territories in the region sought to conserve FSAs with various management measures including temporal and spatial closures, quotas and harvest limits, species bans, and gear restrictions. Unfortunately, many nations lack the human or financial resources to assess or monitor FSAs and their associated fisheries. In the few areas where assessment and management of FSAs has been temporally consistent, in the Cayman Islands, Cuba, Belize, Florida and the US Virgin Islands, they have shown signs of recovery, but for others it is unknown. In spite of many challenges, FSA monitoring and management has been a central topic at GCFI. Indeed, GCFI has long been a lead organization in promoting FSA research and communication in the wider Caribbean.

A. Brief history of FSA focus within GCFI

Starting with the 1979 contribution of Olsen and La Place, there has been a steady increase in FSA focus at GCFI. Based on a rapid search through the GCFI proceedings using the search term, 'spawning aggregation', we enumerated the number of manuscripts (not including abstracts, posters, or spawning of non-finfish species) on the subject between 1951 and 2018. The results illustrate an increasing focus on FSAs over time (Figure 3). Starting just after the formation of the global Science and Conservation of Reef Fish Aggregations (SCRFA) organization in 2000, GCFI held sessions of oral presentations on FSAs nearly every year since then. These were generally sponsored by SCRFA, The Nature Conservancy, and other groups.

At GCFI 61 in 2008, a special session and panel discussion was hosted, and the sessions have now become a mainstream part of the GCFI annual conference.

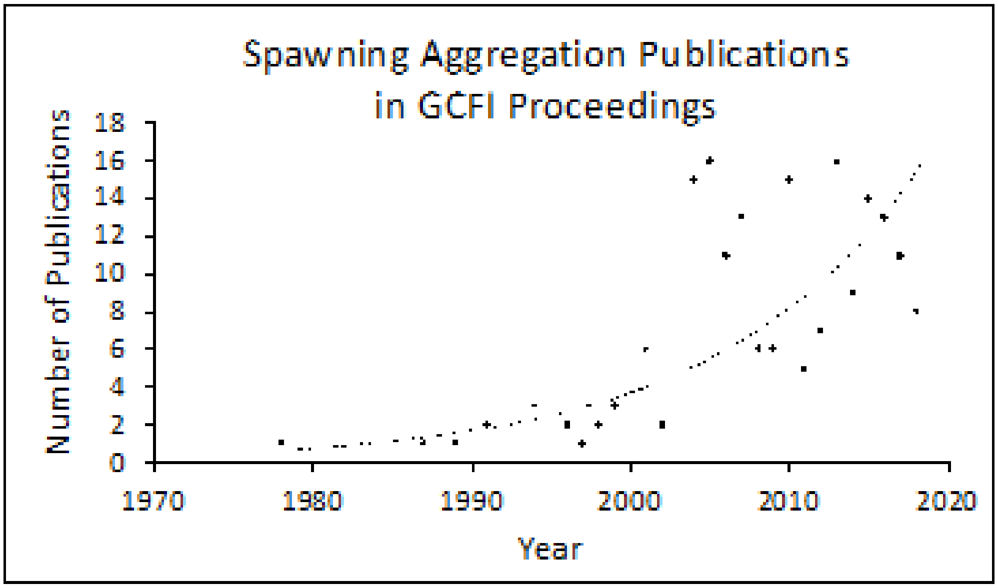


Figure 3. The number of FSA-related publications in GCFI proceedings 1978-2018.

SCRFA constructed a database to house information on FSAs throughout the globe, which now contains over 900 records. In spite of individual efforts around the basin, and the development of the regional database, harmonization of monitoring techniques and synthesis of regional information has been a continuous challenge. To address the data gaps in the biogeography of FSAs, the National Science Foundation's Virgin Islands Established Program to Stimulate Competitive Research (VI-EPSCoR), sponsored a regional Workshop at GCFI in 2009 entitled, "Characterization and Prediction of Transient Reef Fish Spawning Aggregations in the Gulf and Caribbean Region", held in Cumaná, Venezuela, during 62nd annual GCFI meeting. The workshop included over 50 participants from 18 countries around the Caribbean. Participants compiled data on the location of multi-species FSAs in their respective regions, the species-specific timing of spawning and conservation status, and reported on the types of information collected through scientific investigations and local or traditional knowledge. The results from the workshop and some additional data gathering were compiled into a summary of FSA status, levels of management, monitoring techniques and conservation measures in the wider Caribbean (Kobara et al. 2013). The paper offered best practice guidelines for various methods to observe, assess, and monitor spawning aggregations.

During the intervening 10 years since the EPSCoR-sponsored workshop, there have been a number of advances in the technologies available for and used to monitor and assess FSAs in the region. The purpose of this workshop in 2019 was to bring together experts from around the region to share best practices and highlight the use of technological advances for FSA monitoring and assessment. The incorporation of advanced technologies may facilitate the efficient monitoring of FSAs which will contribute to their management, enforcement, and ultimately, recovery for the species that aggregate to spawn throughout the Gulf and Caribbean region.

B. Workshop audience, scope, and objectives

Invitations to the workshop were distributed through the GCFI conference website and through the GCFI email listserv as well as notifications through other regional collaborative networks and via word-of-mouth. The intended audiences were students and young professionals, agency scientists, researchers and analysts, fishers, and resource managers.

The format of the workshop was a mix of keynote presentations, small group breakout discussions, presentations of emerging technologies, and breaks to encourage networking and informal discussions. This report summarizes the activities and outcomes from contributions by 51 participants representing 12 countries (see Appendix B).

The overall goal of the workshop was to review progress made since the 2009 GCFI workshop on FSAs in the Caribbean (Kobara et al. 2013) and address priority recommendations identified in the Western Central Atlantic Fishery Commission (WECAFC; 2018) report, specifically to "Develop and activate a *regional cooperative monitoring system for FSAs*" and "Share technical capacity for FSA identification, characterization, monitoring and conservation." Addressing these recommendations, the two primary goals of the workshop were to: (1) Enhance the scientific capacity within the GCFI community and establish best practices in conducting research and monitoring of reef fish spawning aggregations (FSAs) using integrated technologies, and (2) Evaluate the scientific data requirements for stock management (e.g., ensuring sustainable populations) and spatial management (e.g., conserving single or multi-species spawning aggregations) strategies for FSAs. To address the goals, the following objectives were identified:

- Summarize the state-of-science of FSA monitoring, assessment, management, and protection of resident and transient spawning aggregations in the region.

- Evaluate and provide guidance on the use of integrated technologies to enhance research and survey operations and reduce sources of uncertainty on FSAs to address various informational requirements for management such as biomass estimation, spatio-temporal variability, and essential habitat.

- Identify the feasibility and limitations (i.e. technical, financial) in deploying technologies, and provide recommendations in designing cost-effective FSA survey programs in support of fishery and ecosystem management decisions.

III. Results from the pre-workshop evaluation

Word cloud of participant responses to the question "What do you hope to achieve by attending the FSA workshop?"

A pre-workshop questionnaire was distributed to better understand the background of the participants, their range of experiences, and their expectations or what they hoped to achieve during the workshop. Participants were working in a range of geographic locations throughout the Gulf of Mexico and the Caribbean (Figure 4), as well as various locations in the Indo-Pacific and Gulf of California. The majority of participants identified themselves as fishery scientists and data collectors; however, there was some participation from the NGO sector, government sector, and the fishing industry (Figure 5). The only area of expertise not well-represented was stock assessment; however, a number of participants have a background in population dynamics. Participants were involved in and/or expressed interest in learning about a wide range of technologies and sampling techniques (Figure 6). Diver visual observations were most frequently used, but passive acoustics, underwater video or stereo optics, tagging studies, and active acoustics were also in use by a variety of participants. Of the potential knowledge gaps determined by the steering committee, participants indicated that the most critical information gap related to detecting and documenting FSA recovery, although other knowledge gaps were also considered important. With regard to workshop expectations, participants expressed a desire to learn novel applications of technologies, expand their network and develop collaborations, and share their expertise while learning from others. Workshop conveners noted that the agenda was structured in such a way to maximize networking opportunities and exchange of information, through a balance of plenary discussions and small group exercises.

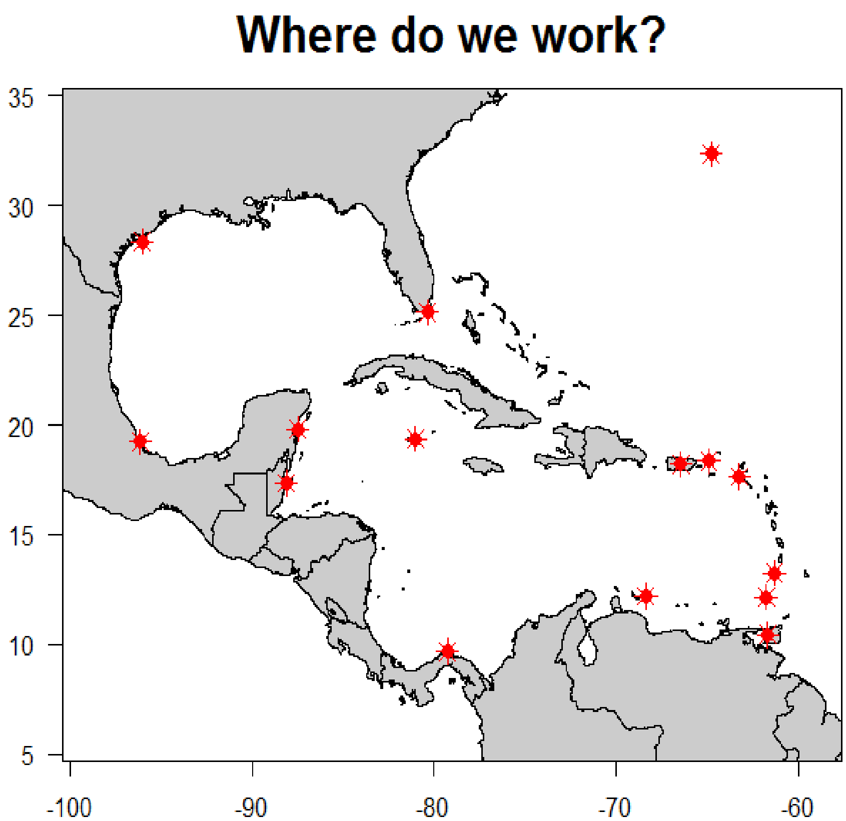


Figure 4. Participants' geographical locations of research or work.

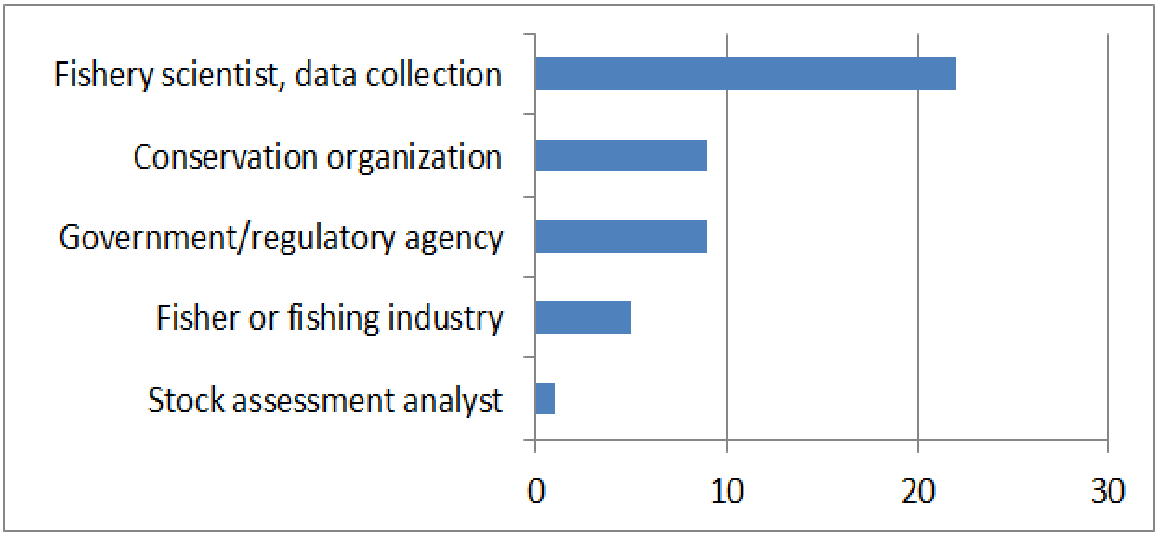


Figure 5. Participant responses to the capacity in which they are involved in fishery management.

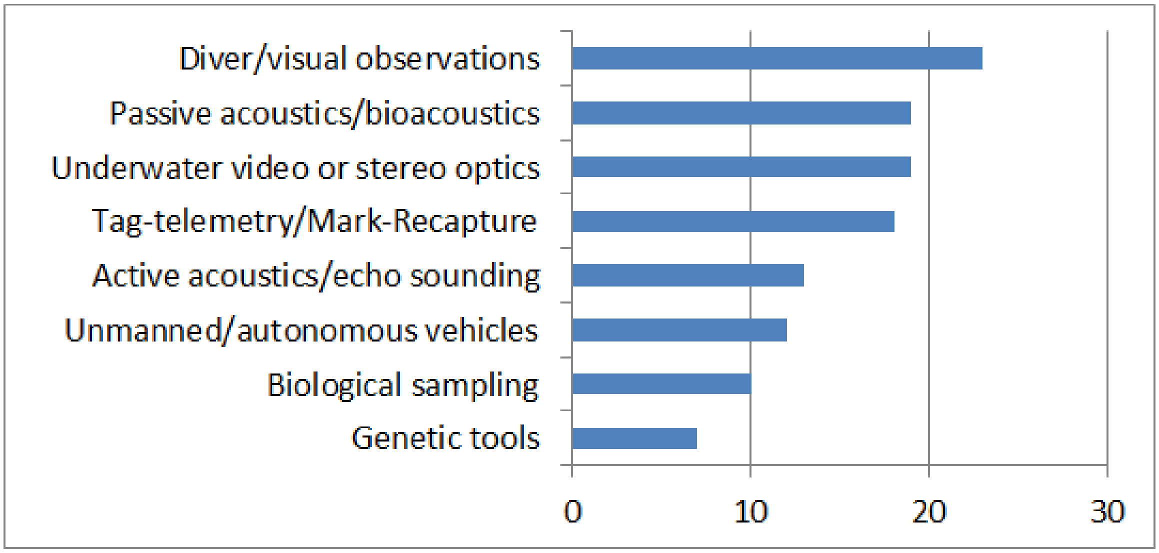


Figure 6. Types of data collection currently ongoing, or of interest to, the workshop participants.

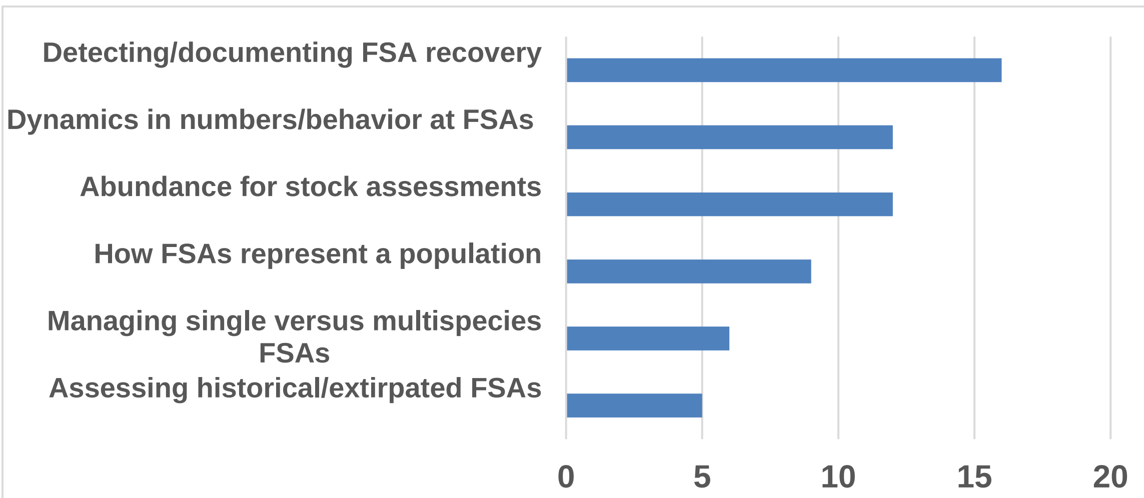


Figure 7. Key research gaps, in order of priority as identified by the participants.

IV. Keynote Addresses: From Data Collection to FSA Management and Conservation

The workshop began with two keynote presentations highlighting two extensive studies of fish spawning aggregations that show how partnerships, intensive monitoring, and rigorous analysis of the dynamics of aggregating species can contribute to informed management strategies to conserve fish stocks.

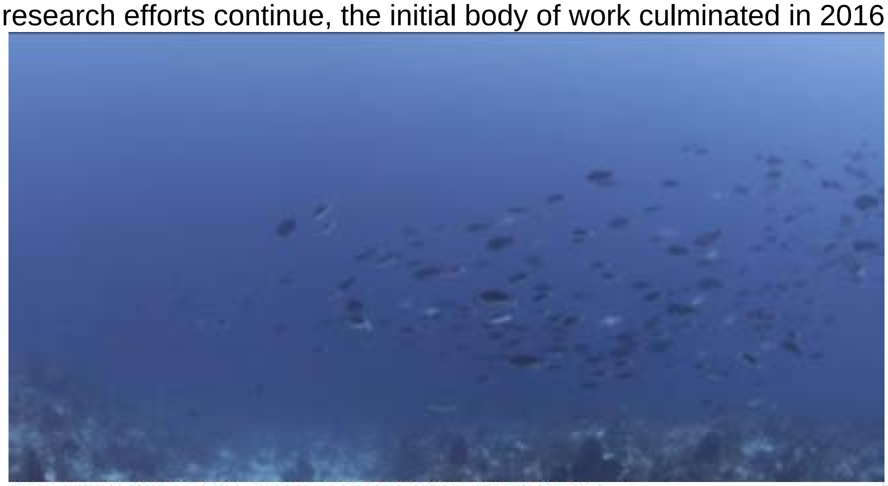
A. Public-private-academic partnership leads to FSA conservation success in Cayman Islands

Scott A. Heppell[1], Christy Pattengill-Semmens[2], Croy McCoy[3], Bradley Johnson[3], Timothy Austin[3], Gina Ebanks-Petrie[3], Phil Bush[3], Lynn Waterhouse[4], Brian Stock[4], and Brice X. Semmens[4]

[1]Oregon State University Department of Fisheries and Wildlife, 104 Nash Hall, Corvallis, Oregon, 97331, USA, [2]Reef Environmental Education Foundation (REEF), PO Box 370246, Key Largo, Florida 33037, USA, [3]Department of Environment, Cayman Islands Government, P.O. Box 486GT, Grand Cayman, Cayman Islands, [4]Scripps Institution of Oceanography University of California, San Diego, 9500 Gilman Drive La Jolla, California, 92093-0202 USA

Abstract

Reef Environmental Education Foundation (REEF) and Cayman Islands Department of Environment (DOE) have collaborated on the Grouper Moon project since 2001. Partnered with scientists from Scripps Institution of Oceanography and Oregon State University, the Grouper Moon Project is the Caribbean's oldest continuous grouper spawning aggregation research program, and represents one of the most advanced, multi-faceted tropical fisheries research programs in the world. This initiative began after the collapse of most Nassau Grouper Fish Spawning Aggregations (FSAs) in the Cayman Islands, but immediately after the discovery of one remaining aggregation at the west end of Little Cayman. In the ensuing 19 years, the team has conducted a combination of research, monitoring, and outreach efforts to generate data and public engagement that aid the development of long-term conservation and management strategies for Cayman Islands FSAs. Research approaches the team has employed include acoustic telemetry, mark-recapture, video census, laser and stereo length measurement, passive and active acoustic sensing, combined with outreach efforts including public talks and documentaries, and an innovative education program aimed at Caymanian K-12 students. While monitoring and research efforts continue, the initial body of work culminated in 2016 with



Spawning aggregation of Nassau grouper at Little Cayman.

substantial new conservation laws aimed at protecting Nassau Grouper FSAs. These regulations include a slot size limit, closed season, ban on spearfishing, and a bag and boat limit. Our results show, among other important facets, that the population on Little Cayman has tripled in size over the last decade, validating our efforts and documenting a great FSA conservation success story in the Caribbean.

Introduction

As documented in this report and elsewhere, Nassau grouper (*Epinephelus striatus*) populations have been decimated throughout the Caribbean, primarily because of fishing targeting the species' annual spawning aggregations (Sadovy et al. 2008, Waterhouse et al. 2020). Similar to the situation in other countries, by the mid-to-late 1980s fishermen in the Cayman Islands were concerned about the decline in Nassau grouper catch, particularly during the winter spawning months. Based on these concerns, the Cayman Islands Department of Environment (DOE) initiated a research program in 1987 to understand Nassau grouper life history and harvest in the Cayman Islands and to make management recommendations based on that information. Nassau grouper harvest collapsed prior to the completion of that work, so no major management efforts were implemented. This changed in the winter of 2001, when a previously unexploited aggregation of Nassau grouper was discovered at the west end of Little Cayman. Substantial harvest during the winters of 2001 and 2002 pushed DOE and the Cayman Islands Marine Conservation Board to implement an 8-year fishing ban for Nassau grouper at all current and extinct spawning aggregation sites (Whaylen et al. 2004, Whaylen et al. 2006). Shortly thereafter, Reef Environmental Education Foundation (REEF), in collaboration with the DOE and academic scientists, founded the Grouper Moon Project (www.REEF.org/groupermoonproject). The Project was designed to develop a research and monitoring plan and make science-based recommendations for the long-term sustainability of Nassau grouper in the territory. Since that initial goal, the project has expanded. Here we detail the science, education and outreach, and policy efforts that have led to a dramatic increase of Nassau grouper in the Cayman Islands (Waterhouse et al. 2020) and to the Grouper Moon Project being one of the most successful marine conservation programs in the entire Caribbean.

Science

Since 2003, the REEF-DOE Grouper Moon Project has pursued a detailed understanding of Nassau grouper spawning behavior (Whaylen et al. 2004; Archer et al. 2012; Wilson et al. 2020), movement (Semmens et al. 2005; Wilson et al. 2020; Blincow et al.[1], in review), larval dispersal (Heppell et al. 2008; Stock et al.[2]), stock structure (Jackson et al. 2014), ecological impact (Archer et al. 2014), population assessment (Taylor et al. 2006; Egerton et al. 2017; Waterhouse et al. 2020) and critically, population change documenting recovery (Heppell et al. 2012; Waterhouse et al. 2020). Over time, as resources have allowed and additional questions arisen, the project has expanded to study the historical aggregation sites on Grand Cayman and Cayman Brac. Results from some of this work is expanded upon below.

Our acoustic tagging results indicate that (1) fish located on Little Cayman stay on Little Cayman, (2) all fish aggregate every year, (3) larger fish aggregate for longer, and (4) while fish

---

[1] Blincow, K.M., P.G. Bush, S.A. Heppell, C.M. McCoy, B.C. Johnson, C.V. Pattengill-Semmens, S.S. Heppell, S.J. Stevens-McGeever, L. Whaylen, K. Luke, and B.X. Semmens. In review. Spatial ecology of Nassau grouper: Insights from tracking a large, long-lived Serranid species across multiple seasons. Marine Ecology Progress Series.

[2] Stock, B.C., A.D. Mullen, J.S. Jaffe, A. Candelmo, S.A. Heppell, C.V. Pattengill-Semmens, C.M. McCoy, B. Johnson, and B.X. Semmens. Unpublished manuscript. 3-Dimensional advection, diffusion, and mortality of eggs and larvae dispersing from a Nassau grouper (Epinephelus striatus) spawning aggregation observed with a novel plankton imaging system.

do aggregate at the west end of Little Cayman on the winter full moon, they move substantial distances along the shelf edge during the spawning season (Heppell et al. 2013). These results indicate that protecting the Little Cayman FSA protects Little Cayman fish, and that a closed season, instead of just a closed area, is the most effective management strategy given the amount of movement outside of the spawning ground itself.

Oceanographic drifter studies demonstrate that protecting the Little Cayman FSA is important to the long-term prospects of Nassau grouper on Little Cayman. Ocean currents on the nights of spawning create substantial sinuosity and eddying, leading to retention of larvae in close proximity to the island shelf edge for at least several days post hatch (Heppell et al. 2008, Stock et al. in prep). Larval fish have a substantial ability to determine their own settlement fate after the first few days of life (e.g. Leis 2015; Hu et al. 2019), and recent genetics data indicate stock structuring among Nassau grouper spawning sites (Sherman et al. 2020). Collectively, this indicates that local recruitment is dependent on a local FSA.

Documenting recovery of a once heavily exploited aggregation is the capstone of our work. Changes in the size distribution gave an initial view that recovery of the population was ongoing (Heppell et al. 2012). Recently (Waterhouse et al. 2020) used nearly 2 decades of observations to document the success of the decades-long efforts of DOE and Cayman Islands Government to restore Nassau grouper to the reefs of Little Cayman. The study also demonstrated that a similar, but slower recovery is ongoing on Cayman Brac. Recovery is not a smooth function; rather, major episodic recruitment events in some years drive stock dynamics (Stock et al. in review). This means that recovery times can be long and conservation efforts need to be sustained.

Education and outreach

In addition to our research and monitoring pursuits, for the last 18 years Grouper Moon collaborators have spent a significant amount of time incorporating outreach and education efforts targeted at stakeholders, schools, local communities, and the public at large. Countless hours were spent by DOE scientists and managers speaking to fishers at public meetings and through one-on-one interactions, addressing questions about the fishery, what we were learning about spawning aggregation dynamics, and why particular conservation and management decisions were being made. These difficult yet critical conversations helped create a path forward for the legislation that was ultimately crafted for the conservation and management of Nassau grouper in the Cayman Islands.

Each year, in conjunction with annual winter Grouper Moon Project fieldwork activities, DOE scientists speak with local print and broadcast media, sharing with the local community information about ongoing activities, conservation actions, and how Nassau grouper are faring in the Islands. In addition to several short PSA-style outreach videos produced over the years (e.g. *Groupers Last Stand*, https://youtu.be/qqnkv38iTy8, which was widely distributed to support extension of the initial 8-year closure to allow time for the comprehensive legislative package), three full documentaries have been produced based on Grouper Moon work. These include *Grouper Moon*, an episode of the US Public Broadcasting System's WPBT series *Changing Seas* (https://www.changingseas.tv/season-4/403/), as well as *The Mystery of the Grouper Moon* (2012; https://vimeo.com/235409714) and *Grouper Moon: The Next Phase* (2019; https://www.youtube.com/watch?v=TfsUsCgCH0A) both by the Guy Harvey Ocean Foundation. Each of these reached a broad audience, with the *Changing Seas* documentary being syndicated across the United States.

Perhaps most importantly, Grouper Moon has had a major focus on providing marine science education to students in Caymanian schools. Led by a dedicated instructional designer along with committed educators in the classroom, lesson plans, live underwater broadcasts, and classroom activities have been designed to help the next generation of Caymanians understand and appreciate how the conservation work being led by DOE and REEF provides a sustainable future for Nassau grouper in the Cayman Islands (https://groupereducation.edublogs.org/about-grouper-education-program/).

Briefly, prior to the beginning of each Grouper Moon research year, workshops on Grand Cayman and Cayman Brac are held to distribute a marine science curriculum with lesson plans for teachers who want to include learning about Nassau grouper in their classrooms. Students learn about the Nassau grouper life cycle, the cultural importance of the Nassau grouper to Cayman Islands heritage, why Nassau grouper are so threatened, the conservation challenges the species faces, and how Grouper Moon Project findings and the government's actions have led to a resurgence of the species in their country. The classroom work culminates during the Grouper Moon Project field season (in January or February), where during our annual field work the Grouper Moon educator web-broadcasts project scientist "research features" live into the classroom. Students are given updates about the project, learn about new technologies being applied in the ocean, and can ask questions directly of the project scientists. The finale is an opportunity for students to interact live with a scuba diver who is broadcasting directly from a coral reef on Little Cayman.

Policy

Following the discovery of the Little Cayman Nassau Grouper FSA in 2001, and subsequent heavy harvest (~4,000 fish) during the spawning periods of 2001 and 2002, the Cayman Islands Marine Conservation Board instituted emergency no-take zones at all known Nassau grouper aggregation sites, albeit only during the spawning season. This eight-year moratorium was designed to provide the DOE with sufficient time to survey the Little Cayman Nassau Grouper FSA and develop an appropriate management strategy. In 2011, at the sunset of the initial MCB action, the MCB renewed the harvest ban for an additional eight years. In 2016, the Cayman Islands government enacted new legislation aimed directly at recovering Nassau grouper, with specific actions informed heavily by the results of the 15 years of Grouper Moon research that had happened to that point. The National Conservation Regulations of 2016 (https://www.gov.ky/) as they apply to Nassau grouper, prohibit harvest of Nassau grouper from December 1 to April 30; create a slot limit allowing harvest only of fish between 16- to 24-inches; limit harvest to 5 Nassau grouper per vessel per day (during the open season), and bans the use of spears in the harvest of Nassau grouper. This is in addition to the extensive network of no-take marine parks that ring the Cayman Islands. At this time, particularly when the 2019 expansion of no-take marine parks around the Cayman Islands is included, the outlook for the long-term sustainability of Nassau grouper in the Cayman Islands is quite positive.

Lessons learned

We have greatly enhanced our understanding of Nassau grouper life history and population dynamics, but most importantly, through the Grouper Moon Project we have created a template for how similar success might be achieved in other countries. While academic scientists can publish papers and non-governmental organizations can facilitate engagement and perhaps advocate for policies, a collaborative approach that includes these entities plus a government agency that seeks to make informed decisions creates a recipe for success. The enduring commitment of DOE and REEF to see this partnership through almost two decades of effort, from the near demise of the Little Cayman west-end FSA to the ascendant recovery of Nassau grouper on Little Cayman, is testament to that. For Grouper Moon collaborators, there was no need to translate science into hopeful policy action, because government, NGO, academic, and industry partners worked together to design, implement, interpret, and act on results in an information-driven manner. These relationships don't just happen. It takes effort on all parties to not just establish but to sustain such an endeavor; however, as we have demonstrated here with the Grouper Moon Project, the payoff is substantial.

Sustained multi-tiered education and outreach is critical to success. From working one-on-one with individual fishers at the docks and in the community, to conducting seminars to the local tourism industry each winter, to developing outreach products, we built a community understanding of, and support for, research efforts and the translation of those efforts into policy. The results are self-evident in the establishment of the largest known Nassau grouper spawning aggregation left in the entire Caribbean Basin.

B. The evolution of monitoring of a commercially targeted fish spawning aggregation: lessons learned from Gulf corvina (*Cynoscion othonopterus*)

Timothy J. Rowell[1,2] and Brad E. Erisman[1,3]

[1]*Marine Biology Research Division, Scripps Institution of Oceanography, University of California San Diego*

[2]*Protected Species Branch, NOAA Northeast Fisheries Science Center*

[3]*Marine Science Institute, The University of Texas at Austin*

Introduction

Fish spawning aggregations (FSAs) have increasingly been acknowledged as important components of the life history of fishes that need to be considered and incorporated into the management of fish stocks, as they contribute to the long-term productivity, resilience, and sustainability of fish populations and fisheries (Erisman et al. 2017). Many exploited fishes such as groupers (Epinephelidae), snappers (Lutjanidae), and croakers (Sciaenidae) are particularly susceptible to overfishing due to their reproductive behavior in which individuals migrate significant distances to form large, transient spawning aggregations at known sites and times (Sadovy de Mitcheson et al. 2008). Fisheries that target transient FSAs focus effort at sites and during periods when fish are present in high densities, resulting in large landings with minimal effort (Sadovy and Domeier 2005). Overfishing FSAs can result in decreased stock sizes, mean lengths, and recruitment, diminished densities and biomass, skewed sex ratios, and complete extirpations of FSAs (Sadovy de Mitcheson and Erisman 2012).

Despite the conservation risks of fishing FSAs, examples of small-scale and commercial fisheries that target FSAs remain numerous globally due the social, economic, and cultural benefits they provide to regional communities and rising demands for seafood to support growing human populations (Erisman et al. 2017). In these situations, research and management activities that broadly seek to demonstrate that fishing FSAs is always problematic and thus should be restricted are impractical and untenable. Researchers are instead tasked to study and monitor FSAs and their fisheries to provide information that can feed into management workflows to develop sustainable fisheries that balance the conservation and utilization of FSAs (Erisman et al. 2019; Heyman et al. 2019).

Harvest of Gulf corvina in Mexico

The Gulf corvina (*Cynoscion othonopterus*) fishery in Mexico is an example where researchers, managers, and fishers were called upon to implement monitoring programs intended to inform and support the balanced management of a highly exploited FSA. Gulf corvina is a large-bodied (grows to 1 m total length and 12 kg body weight; Gherard et al. 2013) sciaenid fish that is endemic to the northern Gulf of California and is targeted by a small-scale, commercial, gill-net fishery almost exclusively during its spawning periods, which occur prior to the new and full moons from February through June (Róman-Rodríguez 2000; Erisman et al. 2012b). Harvested for centuries by indigenous communities along the Colorado River Delta, the modern corvina fishery began in the early 1990s and harvests an average of 3600 tons (~1 million fish) in less than 30 days of fishing effort at the only known FSA site of the entire species, which occurs inside the Upper Gulf of California Biosphere Reserve (Erisman et al. 2019). Concerns over the sustainability of the fishery have existed since its infancy, as identical fishing practices in the same location led to a complete fishery collapse and near extinction of the Totoaba (*Totoaba macdonaldi*) several decades prior (Cisneros-Mata et al. 1995). However, the corvina fishery represents the principal source of revenue for coastal communities in the Upper Gulf for those months and the main source of fish for cities throughout Mexico during the Easter season, making the possibility or support for full protection of its FSA an unlikely management option.

Fishery monitoring efforts

Monitoring efforts began under the leadership of Martha Róman-Rodríguez and colleagues, whose surveys and collections produced the first technical report on the biology and fishery of corvina (Róman-Rodríguez 2000). However, research activities escalated in 2008 when researchers from the Gulf of California Marine Program (GCMP) with expertise in FSAs were approached by the Mexican government to address sustainability concerns surrounding the fishery (Table 1). The following year, the GCMP initiated a cooperative research program in partnership with local fishing cooperatives, government officials, and regional NGOs focused on gathering fishery-dependent biological and catch information. Initial activities focused on the use of GPS trackers to understand spatiotemporal activities in fishing effort and catch, fishery-dependent surveys to characterize length structure and selectivity, biological sampling of landed fish to generate life history information that could feed into fishery assessments (e.g. age structure, growth rate and maturity, fecundity, spawning periodicity), and monitoring of cooperatives and processing plants to delineate daily and seasonal trends in catch rates, ex-vessel revenues, and market prices. Such efforts led to a series of reports and publications that summarized fishing, spawning, and life history patterns of the corvina and the first estimates of potential impacts of the fishery (Paredes et al. 2010; Erisman et al. 2012a, b; Gherard et al. 2013; Erisman et al. 2014; Erisman et al. 2015).

Collective efforts to monitor, assess, and manage the corvina fishery escalated further in 2011 when organizations from academia, state and federal government, the fishing sector, and the conservation sector came together to form the Corvina Technical Group (GTC). Members of the GTC were tasked with supporting the National Fisheries Commission (CONAPESCA), the National Fisheries Institute (INAPESCA), and the National Parks Commission (CONANP) on the management of the corvina fishery and the Biosphere Reserve. This process led to the creation of a regional biological monitoring program that surveyed and sampled landed corvina (e.g. length, sex, reproductive condition, age) to monitor trends in the corvina population in relation to fishing activities, management policies, and environmental conditions. It also resulted in an official administrative monitoring program that attempted to track the fishing effort, landings, sales, and export of all corvina as a means to support the enforcement of the annual harvest quota and improve the collective understanding of the social and economic forces surrounding the fishery. Inter-agency collaborations during this period were successful in synthesizing all biological, fishery, and socioeconomic data to produce several data-poor assessments on the status of the fishery (MacCall et al. 2011; Apel and Erisman. 2012; Erisman et al. 2012a, b; Gedamke and Erisman 2012; Wielgus and Erisman 2012; Erisman et al. 2013; Reulas-Peña et al. 2013; Erisman et al. 2014; Ortiz et al. 2016; Erisman et al. 2019).

Table 1. Timeline of monitoring effort and methodologies by researchers studying the Gulf corvina (Cynoscion othonopterus) fish spawning aggregation and fishery. Gray bars indicate years of corresponding monitoring for each category.

Monitoring Category	1987-2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Length/Age Structure of the Fishery	■	■	■	■	■	■	■	■	■	■	■	■
Individual Growth Rate Modelling	■	■	■	■	■	■	■	■	■	■	■	
Spawning Seasonality	■	■	■	■	■	■	■	■				
Reproductive Development and Fecundity	■	■	■									
Spawning Periodicity and Migration Patterns		■	■	■	■	■						
Spatio-temporal Patterns of Fishing Activity (GPS Tracking)		■	■	■	■	■	■	■	■			
Commercial Prices, Revenues, and Market Chains			■	■	■	■	■	■	■			
Fishery Assessments				■	■	■	■	■				■
Sound Production and Spawning Activity (Passive Acoustics)					■	■	■	■	■			
Total Landings and Sales Volumes (for Enforcement of Quota)					■	■	■	■	■	■	■	
FSA and Population Abundance (Active Acoustics)							■	■	■			
Effects of Climate and Environmental Variation								■	■	■		

Fishery monitoring results

The results of the first five years of monitoring and assessments revealed some important patterns and trends. The results of GPS tracking of fishing effort and surveys of landings indicated a tight coupling of fishing effort and fish spawning during the outgoing tides in the Colorado River delta across multiple years, providing further credence that the fishery is largely focused on time of spawning and extracts fish actively spawning (Erisman et al. 2012b). Total reported landings from 2009-2014 fluctuated between ~2000-4000 tons but closely tracked the total allowable catch quotas established in 2012 and onward, indicating that the stock could support the regulated quotas during this period of time (Figure 8a). However, the length and age composition of the catch indicated that the corvina population was highly truncated such that 80% of fish older than age 4 were removed each year, and no fish survived past the age of 7 (Erisman et al. 2014). Moreover, a steady decrease in mean total length of capture was detected (Figure 8b), raising suspicions that the stock biomass or at least the biomass of larger size classes was starting to diminish given the continued use of standard gill net mesh sizes of 14.6 cm. Analyses of growth rates and reproductive patterns indicated that the fishery largely targeted mature fish of ages greater than 5 years and largely excluded spawning capable individuals of age 2-4 years during the period of 2009-2014. The exclusion of younger spawning individuals in the fishery provided support that the size regulation of 65 cm was well founded and could help facilitate a high spawning potential ratio (SPR) of the stock and mitigate the effects of heaving fishing pressure on recruitment if the periodicity of spawning activity was assumed to be equal across age classes. However, research on other closely related species of *Cynoscion* have demonstrated that older fish spawn more frequently than younger fish, which if true for corvina, would reduce the predicted SPR by more than half and identify the fishery as highly unsustainable (Erisman et al. 2014). The collective results of initial fishery assessments all indicated that the corvina population was overfished and susceptible to persistent overfishing due to massive harvesting of spawning fish each year inside the Biosphere Reserve (e.g. Ruelas-Peña et al. 2013; Erisman et al. 2014; Ortiz et al. 2016).

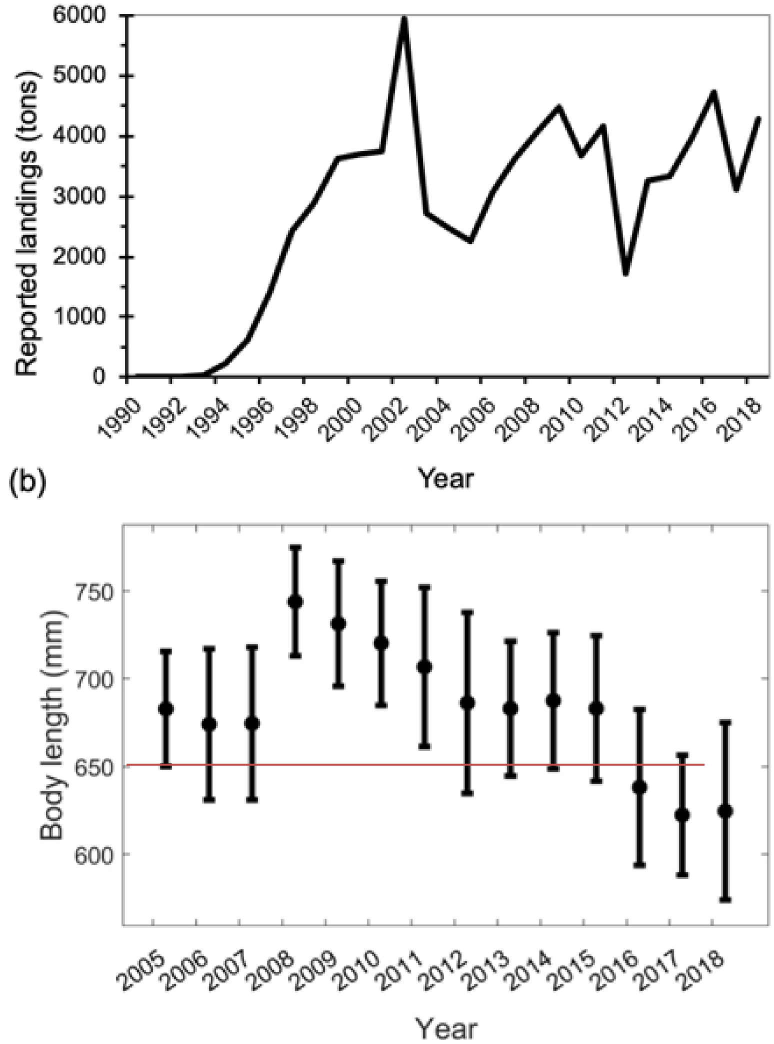


Figure 8. (a) Total reported landings of the Gulf corvina fishery from 1990 to 2018, and (b) mean total length of capture from 2005 to 2018. The 65 cm regulation of minimum total length of capture is indicated by the red line. Data and figures adapted from Erisman et al. (2020).

Acoustic survey efforts

While the results of initial fishery assessments indicated overfishing and an overfished population, the catch and population data collected from fisheries-dependent surveys still lacked the ability to provide a reliable index of stock biomass to set sustainable harvest limits. Briefly, catch data were thought to suffer from extreme hyperstability due to the aggregating behavior of both fish and fishers, making estimates of stock biomass and maximum sustainable yield based on these data unrealistically high (Erisman et al. 2012a, 2014). Therefore, we sought to develop a proof of concept to estimate fish biomass using passive (hydrophone) and active acoustic (echosounder) technologies. From previous efforts, sound production during spawning periods by corvina was observed to be extensive and had the potential to be used to map the dimensions of the FSA and investigate if empirical relationships existed between sound levels and fish density (Erisman and Rowell 2017). During the outgoing tides in the months of March and April 2014, two hired fishing vessels were used to survey the FSA; an active acoustic echosounder was configured on the first vessel to estimate corvina densities and abundances present during each survey, and the passive acoustic equipment was installed on the second vessel to record the sounds produced by corvina. The echosounder-equipped vessel conducted transects across the Delta channel, while the passive acoustic vessel recorded ambient sound along each echosounder transect prior to its completion, allowing for a coupling of measurements in space and time. Echosounder data were calibrated and analyzed to estimate fish densities and abundance via echo counting; biomass was also estimated from echosounder results. Passive acoustic recordings were analyzed and filtered to calculate received sound levels attributable to corvina chorusing. Coupled measurements of fish density and sound production levels were mapped, compared, and modeled.

Acoustic survey results

We observed large aggregations comprised of more than 1.5 million fish, equivalent to 2,145 metric tons, and elevated sound production levels distributed over 25 km of the delta. Maps of density and received sound levels over the frequency of choruses depicted similar spatial patterns on the outgoing tides, indicating that sound levels effectively mapped the distribution of the spawning aggregation (Erisman and Rowell 2017; Rowell et al. 2017). The relationship between sound levels and density varied within surveys but stabilized during the two-hour period of peak spawning (e.g. high tide to two hours after high tide), resulting in an equation to estimate densities from received sound levels during a two-hour period in which calling rates were inferred to be stable. The results of this study indicated that echosounder surveys were feasible to estimate the distribution, density, abundance, and biomass of the spawning stock and that when relationships are known, fish densities and biomass could potentially be estimated from recorded levels of fish sound production at the site in future surveys. While limited in nature, this feasibility study provided a first snapshot of fish biomass and a proof of concept that could be applied over multiple areas and years to help monitor the stock in relation to ongoing fishing effort and provide timely information for managers (Rowell et al. 2018).

Lessons learned and thoughts for the future

After nearly a decade of monitoring and testing various tools to help provide pertinent information and techniques to researchers and managers, trends in total reported landings remained fairly stable near the established total allowable catch while mean length at capture continued to decrease up until 2018 (Figure 1). From 2016 through 2018, the mean length of capture was below the minimal total length regulation of 65 cm, and fish above 75 cm (i.e. 6+ years of age) were incredibly rare in the population and landings (Erisman et al. 2019). Inconsistencies between reported landings and length at capture data provided warning signs that the biomass of the stock was likely decreasing, and hyperstability in fisheries dependent data used to calculate the annual harvest quota allowed overfishing to continue while masking population declines. Moreover, results from GPS monitoring of fishing activities indicated that the spatial extent of fishing activities and the area over which the FSA occurred decreased steadily (GCMP unpublished data). However, during this period, there was increased political pressure to allow the corvina fishery to continue, as conservation efforts surrounding the protection of the critically endangered vaquita porpoise (*Phocoena sinus*) and the Totoaba led to temporary gill net bans and heavy fishing restrictions on other gill net fisheries in the region (Aburto-Oropeza et al. 2017).

Despite the compilation of a large volume of information on the biology of the corvina, spatio-temporal interactions between its spawning behavior and the dynamics of its fishery, multiple assessments pointing to a declining fishery and population, and the creation of several novel approaches for monitoring the FSA and estimating stock biomass (*see* Rowell et al. 2018; Table 1), the stock biomass and the annual harvest quota continue to be calculated using catch data as mandated by the laws and regulations governing the management of the fishery. This discrepancy points to ongoing challenges with the integration of FSAs into traditional fishery management processes. However, we have recently completed a new assessment of the fishery indicating that brief, temporal closures of the fishery during peak spawning days and periods could increase resilience (by enhancing egg production per recruit) while maintaining large, profitable catches (Erisman et al. 2019). Notably, this management option was explored at the request of regional fishing sector, reinforcing the value and importance of fisher ecological knowledge and participation in all aspects of fisheries research and management. Lastly, the otoliths and length data collected continuously from 1993 through 2017 were analyzed to assess the influence of climatic and environmental variability on fish growth and fisheries production (Reid 2017), which may be important for consideration in the future management decisions.

Acknowledgments: The success of our cooperative research program on the corvina fishery has involved the participation, support, and leadership of many people, including: O. Aburto-Oropeza, C. López-Sagástegui, G. Paredes, I. Mascareñas-Osorio, J.J. Cota-Nieto, M. Moreno-Báez, M. Román, H. Lícon-González, A. MacCall, R. Fujita, A. Apel, V. Jiménez-Esquivel, C. Tirado, R. Franco, D. Demer, J. Hyde, K. Gherard, J. Montañez Rivera, C. Gonzalez-Abraham, P.A. Hastings, A. Montes Zamudio, J. Cabrera Rivera, E. Cabrera Rivera, Y. Flores, J. Vázquez, L. Pérez, V. Corrales, H. Ruiz, A. Domínguez, R. Carilllo, A. García, G. Hinojosa, A. Grüss, E. Reed, C. Biggs, K. Rowell, A.F. Johnson, T.S. Sessions, J.P. Zwolinski, S. Freeman, M.J. Buckingham, J.S. Renfree, S.A. Mau, S. Gedamke, J. Gedamke, and many others. Additional support was provided by the Gulf of California Marine Program at SIO, Grupo Tecnico Corvina (GTC), CBMC, CONAPESCA, INAPESCA, CONANP, CEDES, NOS, AGS, IAES, EDF Mexico, the World Wildlife Fund Mexico, and NOAA/NMFS Southwest Fisheries Science Center. Funding for the program was provided by the NOAA Acoustics Program, Walton Family Foundation, David and Lucile Packard Foundation, EDF Mexico, WWF Mexico, The University of Texas Marine Science Institute, and the National Academies of Sciences, Engineering, and Medicine. We especially thank the fishers and community members of El Golfo de Santa Clara, San Felipe, El Indiviso and other coastal communities in the Upper Gulf for their unrelenting support and collaborative efforts to create a sustainably, co-managed fishery for the Gulf corvina.

V. Breakout session: How do we document trends in FSA abundance and use them for management

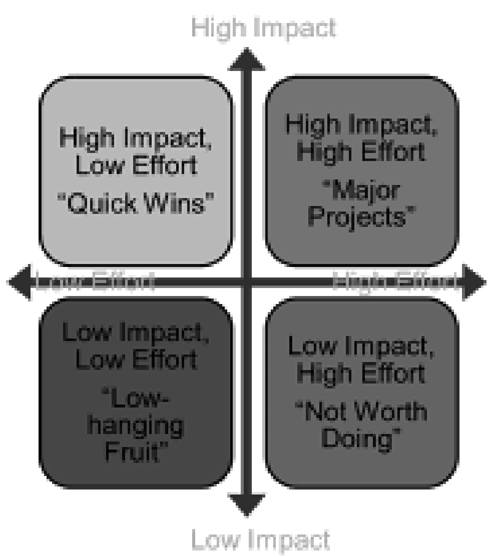
This initial breakout session was framed by four key question sets that were formulated by the workshop steering committee. These questions capture long term goals of FSA working groups and identify gaps in the understanding of dynamics in FSAs throughout the Caribbean and Gulf of Mexico. The four question sets address concepts in quantitative population assessments, uncertainty in spatial location and timing of FSAs, and tracking recovery of FSAs.

- Are data from FSAs for stock assessments a valuable end goal? What are the expected data streams that would be most useful to integrate into a stock assessment process?
- How representative is one or a few FSAs to the population? What percentage of the fish in an area use a particular FSA? What are the challenges with assessing and managing single versus multi-species aggregations?
- How do FSAs change over time, and can it be related to management actions? How do the dynamics of the aggregation change in terms of use, do aggregations reoccupy other sites?
- What does a recovering FSA look like? What is the meaning of trends in abundance? What monitoring design is required? What is the fate of an extirpated FSA? What do zeros actually mean?

As these questions have formed the basis for FSA programs along a continuum of funding resource levels and duration, we addressed each set of questions using the following guideposts to help review the current state of knowledge, the relevance of the question, and availability of emerging tools and technologies to help fill data gaps that could better address the questions.

- What is known about this topic? Provide examples.
- How important is this gap for improving management of the species?
- What technologies are available to address this gap?

Participants were divided into four groups and worked within their groups through the guideposts, listing examples and references and then identifying approaches that could be used to fill data gaps. Approaches were organized in the form of an effort-impact table, to identify the most easily achievable and priority activities. For example, if an abundance index for a particular stock assessment was thought to have high impact, and a cheap technology could be suggested for collecting the data to develop the index, such an activity was considered to fall within the "Quick win" category.



Taken from https://www.fireflyfacilitation.com/create-a-plan-using-the-impact-versus-effort-grid

A. Are data from FSAs for stock assessments a valuable end goal? What are the expected data streams that would be most useful to integrate into a stock assessment process?

This discussion revolved around the use of data collected at FSAs in providing information for stock assessment purposes. Initially, participants wished to clarify exactly what was intended by the concept "stock assessment," and it was agreed upon that this should include any type of analysis or model intended to determine the status and trends of a population. There was a wide range of opinions on whether or not data for stock assessment was a valuable end goal for FSA monitoring, and this was largely dependent on the current state of FSA monitoring and management in the different participants' regions. Generally, monitoring with an eye toward data for stock assessments as an end goal was not thought to be the first priority. For regions lacking any sort of regular data collection related to aggregations, FSA site discovery and characterization were thought to be more important priorities. For sites that had been characterized and regularly monitored, however, it was thought that providing data for stock assessments could be an objective of improved monitoring schemes.

An assessment is any type of analysis or model intended to determine the status and trends of a population.

Whether or not FSA monitoring could yield useful data streams for stock assessments was thought to be largely case-specific, and was dependent on the isolation and scale of the FSA. These traits largely determine whether the population characteristics at the FSA could be used to make inferences about the larger population. If single FSA sites are not thought to be characteristic of the larger population, additional information is needed on the number of FSAs within the population domain, as well as basic fisheries data such as catch data to understand when and where peaks in landings occur. However, when it has been established (through tagging or acoustics studies) that an FSA can be considered representative of a population unit, there are multiple data streams that can be useful for stock assessment. In such cases, the most useful metrics were identified as: sex ratio information, length-frequency distributions, relative spawning stock biomass estimates, and total abundance estimates.

B. How representative is one or a few FSAs to the population? What percentage of the fish in an area use a particular FSA? What are the challenges with assessing and managing single versus multi-species aggregations?

It was broadly recognized that there is a gap of scientific information regarding the basic knowledge needed to answer questions about how FSAs represent dynamics of a population. Nonetheless it was agreed that it is key to understand how representative the FSA is to be able to gauge whether to protect a particular FSA and how that affects the rest of the population. For fisheries managers it is important to know what strategy would be best to protect any particular FSA, either a closed area versus a closed season; this largely depends upon what is known about the FSA relative to the population. On the same note it is important to know how many FSAs need to be identified and protected to maintain the population. Hence this gap affects the analysis that goes into the design of effective spatial planning, monitoring, and potentially stock assessments either by use of a spawning index or other measures of reproductive capacity during the FSA.

The group highlighted the importance of developing linkages between an index of reproductive output due to an FSA with the recruitment of that species to the population. Understanding the source-sink dynamics and the relative isolation of an FSA were highlighted as key questions. Furthermore, while the scientific questions themselves are important, it is equally important to communicate the benefits of FSA protection to fishers, managers, and the public. For fishers it is important to know who is catching these fish that are generated at a given FSA. At a regional scale it is imperative to know if the FSA is in fact seeding the population of a neighboring jurisdiction or not, which can become a political discussion in regional forums. It was proposed that more support may be gained for management or protection of a particular FSA if there is evidence of the strength of the link between FSA and the population across geopolitical boundaries.

At its core the question is primarily focused on behavioral ecology for which there is little empirical data available. The degree of site fidelity or FSA homing behavior of fishes is highly variable by both species and location, making them inherently difficult to study. Nonetheless, it is an important question to address to be able to design proper monitoring to evaluate fisheries management and conservation. Further complicating understanding of how FSAs function, there may be depensatory effects (Allee) that impact the formation and reproductive success of FSAs. For example, once abundance at an FSA declines, the location may not be positively impacting population dynamics. In these situations, it would be recommended that additional FSAs be included in a network of MPAs or other spatial strategies to increase the likelihood of population recovery using spatial management strategies.

Sites where FSAs occur seem to have an important geographical characteristic such as ocean currents, geomorphology, or other habitat criteria. Understanding the mechanisms that make the FSA sites an attractive area, either oceanographical or environmental, will help address this question, since the hydrodynamics of the site may determine the degree of connectivity throughout the region. Also, the design of networks of MPAs may depend on the presence of the geographical features prone to have FSAs as a planning tool for surveys or protection. For example, the placement of an MPA around an FSA could not be enough to maintain the population, making other measures necessary. If certain sites support multi-species FSAs, then those can be protected year-round, making the potential benefits greater for one site instead of multiple species-specific sites, and in theory making the enforcement and monitoring more cost-effective. It was suggested that combinations of different technologies may be needed to answer this question; for example, to determine the timing using passive acoustics and then design a survey to sample directly with any of the other techniques for direct observation. Some technologies or methods that could be applied to the study of how FSAs represent the population include:

- High resolution or kinship genetics related to population structure to link recruits and FSA (High impact/high effort)
- Otolith microchemistry to try to determine the different locations, if they have different chemical signals, from which recruits to the FSA come (High impact/high effort)
- Chemical tagging of larvae to see where they go (High Impact/high effort)
- High-resolution oceanographic models, in combination with plankton tows and genetics (Low impact/low effort)
- Optical methods to determine the different species spawning (High impact/low effort)
- Tagging and re-sighting of spawners to determine the proportion of the population that arrives at an FSA (Low impact/low effort)
- Know the timing of the FSA to be able to survey effectively (High impact/low effort)
- Active acoustic methods to map and detect aggregations (High impact/low effort)
- Analysis of logbooks and VMA during spawning season to help locate areas of FSA for certain populations (High impact/low effort)
- Recruitment dispersal patterns (High impact/high effort)

C. How do FSAs change over time, and can it be related to management actions? How do the dynamics of the aggregation change in terms of use, do aggregations reoccupy other sites?

The abundance at a spawning aggregation changes over a continuum of temporal and spatial scales which can result in problematic conditions to stage monitoring and management environments. Workshop participants discussed the state of knowledge of the spatio-temporal dynamics of FSAs, but time did not allow for discussion of whether FSAs would reoccupy other (assumed formerly extirpated) sites. Participants first summarized the drivers and temporal scales over which observed changes in numbers of individuals at an aggregation occur. Clearly, for transient spawning aggregations, the numbers of individuals at the aggregation site changes significantly from a few solitary individuals to hundreds or thousands of reproductive adults. For well-studied species and even in limited regions, formation of aggregations is often predictable by season and lunar period. Oceanography, currents, and tides may also cause variation in the numbers of individuals at an aggregation site. Climate change may also cause variation in numbers as ocean temperatures increase and allow for spatial expansion of thermal regimes suitable for some species, or shifts in initiation of aggregation formation in the season. For example, red hind in Bermuda have been observed forming aggregations earlier in the year (Pitt et al. 2018). Fishing impacts, whether it be fishing techniques and pressure, or implementation of fishing restrictions and other management actions, can also cause variation in abundance.

Participants then identified the methods and technologies that could be used to assess numbers of individuals at an aggregation, and also measure the magnitude of the environmental or other external drivers that may be causing numbers to change. Annual collection of life-history parameters such as length and age at maturity were recommended to assist in detecting changes in population vital rates that impact abundance trends. Biological samples may provide some of the lowest cost methods for assessing dynamics of FSAs--for instance, length composition from landings data may indicate recruitment of younger age classes. Directly observing and counting individuals in aggregations remains one of the most commonly applied tools. For other techniques, costs can be prohibitive. For instance, scientific SCUBA surveys are considerably more expensive than utilizing cooperating fishers to conduct citizen-science assessments, when possible. Tagging for mark-recapture studies is another method that could be used to detect changes in abundance. The highest cost and highest impact methods identified were through the use of autonomous platforms such as wave gliders with sensors such as passive acoustics (e.g., courtship calls) that can enumerate individuals or active acoustics to detect locations of high densities (e.g., acoustic backscatter scaled to densities and abundance). Other high-cost and effort methods that have moderate impact include egg sampling to measure output of spawning and e-DNA that may indicate presence of individuals and spawning activity.

It will be important to consider adaptive management rather than managing aggregations for recovery to a baseline in the past that may no longer be achievable due to climate change.

There was also recognition that climate change and warming ocean temperatures may shift the timing of aggregation formation or allow for poleward expansion of species that aggregate. Asch and Erisman (2018) report on a modeling exercise that projects the poleward movement of reef fish aggregations based on expansion of suitable thermal regimes. But availability of suitable habitat may not exist in these new areas. Red hind in Bermuda are forming aggregations extending longer than the current temporal closure that begins in April. Therefore, it will be important to consider adaptive management rather than managing aggregations for recovery to a past baseline that may no longer be achievable due to climate change.

D. What does a recovering FSA look like? What is the meaning of trends in abundance? What monitoring design is required? What is the fate of an extirpated FSA? What do zeros actually mean?

Discussion focused directly on the monitoring techniques than can help assess FSA recovery. These techniques could be used to assess trends, but the group did not delve into the interpretation of data into trends.

Participants first summarized the key features that are associated with a recovering FSA. First and foremost is the increase in biomass driven by an increase in abundance and changes in the size distribution of spawning fishes and complexity at the ecological scale. Such increases could also reflect the influx of new recruits joining the existing population, evidenced by increase in fish of smaller size classes. As a consequence, the spatial distribution of the aggregation and biodiversity increases at the FSA site. This includes the presence of predators foraging on both the eggs and the aggregating species. Participants also suggested that an increase in spawning rushes and fertilization success was indicative of a recovering FSA. Changes in size distribution can also be assessed through fisheries dependent survey, for example fishers' interviews could provide a baseline on the status of the ecosystem before any sign of recovery.

Participants also discussed the importance of reporting the recovery status of an FSA to management and focused on whether management of the FSA is leading to recovery. The answer to that question is key to management decisions and evaluation of their effectiveness and any further actions that should be taken.

> The main question is whether management of the FSA is leading to recovery.

The methods and technologies to assess the key features presented above were discussed and then ranked in the order of the least to the most expensive. The lowest cost approach was thought to be SCUBA based fish surveys (both recreational through citizen science projects such as REEF surveys and scientific divers), followed by SCUBA camera surveys, drop camera surveys, and evaluations of fish landings. Diver surveys can also include observation of successful spawns as well as estimates of population size structure using stereo video cameras or video cameras mounted with parallel laser lights. Mark and recapture studies can assess changes in population size frequency distribution, growth rates of recaptured fish, estimates of population size, the increase in spatial distribution, and the sighting frequency.

Relatively more costly technologies include echosounder surveys used to assess increases in volume backscatter and in the structure of target strength (TS) indicative of increases in the size distribution of spawning fish. Passive acoustic monitoring could also provide indices of recovery through a measure of reproductive behavior by measuring changes in the rates and magnitude of sound production at a FSA. More expensive technology includes vehicle-based tools such as ROVs, AUVs, and towed vehicles with a suite of instruments. The ultimate approach that was proposed consisted of setting up a Long-Term Ecological Research program like those funded by the US National Science Foundation. A comprehensive study would include all of the above technologies as well as plankton tows and ocean and biophysical modeling to simulate recruitment dynamics.

VI. Overview of emerging technologies for FSA assessments

The second day of the workshop was initiated by reviewing the major themes that emerged from discussions during the previous day. A morning plenary session was dedicated to an overview of the state-of-science for selected emerging technologies that can be used to sample and assess FSAs, which included: autonomous systems, passive acoustics, and machine learning. Following is a brief overview of each of these technologies, with respect to potential for FSA monitoring and management applications.

A. Autonomous systems

David Demer[1] and Laurent Cherubin[2]

[1] NOAA National Marine Fisheries Service, Southwest Fisheries Science Center, San Diego, CA USA, [2]Florida Atlantic University, Boca Raton, FL USA

Fish in a variety of aquatic ecosystems are commonly studied, enumerated, and monitored using remote sensing techniques that are increasingly deployed from autonomous sampling platforms. For example, hydrophones, multifrequency echosounders, and numerous other sensors are now deployed from unmanned surface vehicles (USVs) powered by photovoltaics and energy from waves (wave gliders) and wind (sail drones) (Figure 9) to detect, map, and monitor fish spawning aggregations (FSAs) and their oceanographic and seabed habitats.

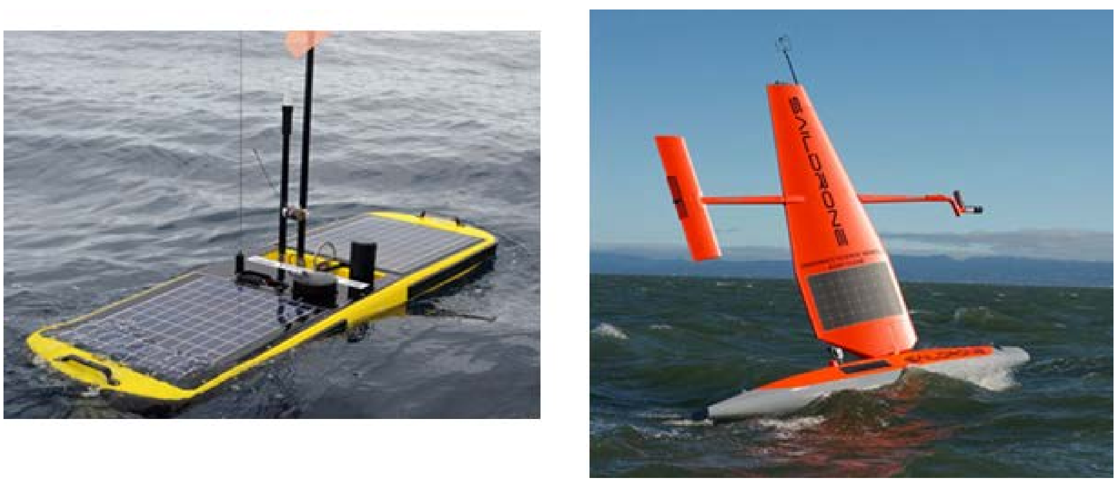


Figure 9. Unmanned surface vehicles (USVs) such as Waveglider (left) and Saildrone (right) use photovoltaic, wave, and wind energy to autonomously collect a variety of atmospheric, physical, and oceanographic data, which may be used to survey and monitor fish spawning aggregations (FSAs).

The USVs may efficiently sample an FSA using information about potential oceanographic habitat that is modeled and monitored using satellite-sensed oceanographic conditions (e.g., https://swfscdata.nmfs.noaa.gov/AST/), or detected using autonomous submersible vehicles such as buoyancy driven gliders or floats (Figure 10). These instrument platforms sample over prescribed depths by modulating their buoyancy, and at prescribed or opportunistic geographic positions using lift generated by wings, or currents, respectively.

Figure 10. Buoyancy gliders (L-R from Teledyne, Bluefin Robotics, and Kongsberg) and buoyancy floats (e.g., right, https://argo.ucsd.edu/) collect oceanographic data over months to years and telemeter the data and their positions to researchers ashore via satellite.

The data collected from USVs are often coupled with information about species and their sizes, known independently from fish caught using conventional techniques (e.g., nets or hook and line) or non-invasively using images from underwater (e.g., stereo video and cameras) potentially deployed from remotely operated vehicles (ROVs) or autonomous underwater vehicles (AUVs; Figure 11) or divers. The combined data provide information about fish behaviors, distributions in time and space, demographics, and abundance.

Figure 11. A high-definition, high-voltage DC remotely operated vehicle (HDHV ROV) and a Fisheries AUV (NOAA SWFSC), both equipped with acoustic, optical, and other sensors to collect data on fish distributions, species, and their sizes, and oceanographic and seabed habitats.

Whether using autonomous instruments and platforms, or small craft outfitted with low-cost acoustical and optical instrumentation, FSAs can be detected, surveyed and monitored using presently available technologies. The technologies are available commercially, through collaborations with industry, governments, and academic institutions. Also, many of the technologies have low-cost versions that may provide the needed information with acceptable levels of accuracy and precision. In addition, some of these technologies are fitted with machine learning tools that enable real-time and effective data analysis for real-time adaptive sampling that suits the transient character of FSAs.

B. Passive acoustics

Michelle Schärer-Umpierre

HJR Reefscaping, Boquerón, PR USA

Passive acoustic methods (PAM) are used to detect, monitor and locate the presence of species that produce sounds during reproductive behaviors prior to or associated with spawning by listening to the environmental soundscape with microphones or underwater hydrophones. This technology has been used in marine ecosystems to classify the source of underwater sounds since the 1950s, and only recently have fisheries scientists and managers integrated this method into marine biological studies. Most of the research to date using PAM has been focused on marine mammals; however multiple species of marine fishes produce sounds for communication in various behavioral contexts, including when they are under threat, feeding, agonism, and mating. Passive acoustics can be used to map spatio-temporal distributions of sound producing fish. It is a non-invasive and non-destructive method to observe behaviors remotely that can be used over long-periods of time to reveal high resolution temporal patterns. Additionally it can be used in habitats deeper than conventional observation methods and it can simultaneously monitor acoustic pollution. The combination of PAM with conventional fisheries techniques provides complementary methods that advance fisheries research. While PAM provides many advantages in understanding fish ecology, there are many limitations as well and those are highlighted in a review (Luczkovich et al. 2008).

Approximately 150 species found in the northwest Atlantic are soniferous (Fish and Mowbray, 1970) including codfishes, drums, grunts, groupers, snappers, jacks, and catfishes. Many of these sounds are accessible via digital libraries such as the sound table in FishBase (https://www.fishbase.se/search.php) or the Macaulay Library at the Cornell Lab of Ornithology (https://www.macaulaylibrary.org/). Within the realm of fish that aggregate for spawning, many of these species are known to produce sound associated with reproductive behaviors and many are part of important fisheries. By detecting the sounds produced during courtship or territorial defensive displays prior to and after spawning, their spawning habitats can be located and mapped and the temporal patterns of behavior studied at high resolution. The application of PAM to study fish ecology has increased in the past decade and expanded to demonstrate other applications including attracting fish with sound playbacks to recruit in degraded habitats (Gordon et al. 2019).

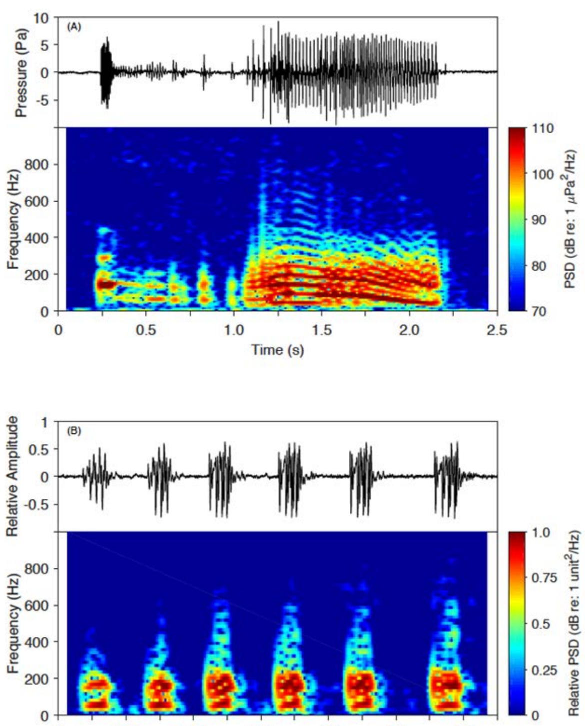


Figure 12. Example spectrogram of sounds produced by Nassau grouper in spawning aggregations.

Various species of groupers that aggregate to spawn are known to produce sound during displays of reproductive behaviors, either courtship or competition for mates (Mann et al. 2009; Schärer et al. 2012a; Schärer et al. 2012b; Mann et al. 2010, Bertucci et al. 2015; Rowell et al. 2018). This combination of visual and acoustic behavior generates species specific sound signals (or calls) that can be detected in-situ and remotely based on their bioacoustics parameters. The physical properties of the sounds such as frequency, timing, and sound structure or rhythm are specific for each species' behaviors, providing researchers with an additional tool to study spawning aggregations (FSA). Field observations have confirmed that some of these sounds only occur during the formation of aggregations for spawning of Goliath grouper (*Epinephelus itajara)*, red hind (*Epinephelus guttatus*), Nassau grouper (*Epinephelus striatus,* Figure 12), black grouper (*Mycteroperca bonaci*) and the yellowfin grouper (*Mycteroperca venenosa*).

Evidence to confirm that a species has sounds associated with a particular behavior, or 'sound truthing' is necessary to be able to accurately interpret passive acoustic datasets. This critical step can be conducted in captivity or *in-situ* as long as the reproductive behaviors occur in captive conditions.

Sound truthing evidence has been collected *in situ* with synchronous audio and video recorders at FSAs that are well studied. Technological advances in optical and acoustical instruments (Loggerhead Instruments, for example) have helped in the collection of data on the behavioral displays at FSAs through synchronization of audio and video recorders over long periods of time at intermittent recording times. This has increased the likelihood of connecting reproductive displays to sound production during FSA activity. SCUBA methods have historically been utilized to understand sound production during mating; however, for some species, sound production is low frequency which prevents divers from detecting them due to the loud sound of air bubbles during exhalation. The use of closed-circuit re-breathers has helped in overcoming this limitation, although the training, risks and equipment are more costly. By deploying instruments that record audio and video simultaneously in areas of known FSAs, the evidence for sound truthing can be collected repeatedly with less interference due to the presence of humans. Once the acoustic signal has been attributed to a species' particular behavior, it can be bio-acoustically characterized to develop different methods of detection in PAM datasets.

In order to use PAM to efficiently detect the presence of particular species and quantify their sounds, the biological and acoustic parameters of the sound must be well described. This requires an understanding of the basic ecological, behavioral, and physiological capabilities of fishes. Some species are capable of producing different types of sounds depending on the behavioral context. Most of the sounds produced during FSAs are associated with reproductive displays, although some threat and alarm sounds are also present when predators attack or divers interfere. In the case of red hind at least five different sound types can be produced (Zayas-Santiago et al. 2019). Courtship has been associated with specific acoustic signals for red hind (Mann et al. 2010) and are heard when males approach females and display to them. Inspection of PAM datasets and captive fish recordings revealed a different acoustic signal when males encounter other males. This sound production is thought to be associated with territorial defense as a prelude to spawning in red hind aggregations that are similar to lek mating systems. In addition, three other types of sounds that are less common were recorded in captivity and *in-situ*. It was previously thought that only males produce sounds, but red hind are protogynous hermaphrodites, therefore they are likely soniferous as females, and at least one sound type recorded in captivity is thought to be produced by females (Zayas-Santiago et al. 2019). This suggests there may be specific functions associated to each type of sound within the complex mating systems that red hind exhibit during FSAs. A similar pattern was observed at a Nassau grouper FSA in Puerto Rico where at least three sound types have been recognized, each associated with different behavioral contexts of Nassau grouper. One is a threat or alarm sound, a second is believed to be associated with courtship displays when

Diver installs a passive acoustic recorder on a coral reef.

males are following and circling a female, and a third less common sound was observed during a male to male encounter as they followed a female and one took over the position of the other, suggesting competition for a position near a potential mate may elicit this sound type (Rowell et al. 2018).

Understanding the variability in sound production from the FSA is a key monitoring component of these reproductive events. Multiple monitoring techniques must be integrated to answer specific questions related to the abundance dynamics at an FSA. At Bajo de Sico, west of Puerto Rico, PAM has been used in combination with internal tagging of Nassau grouper with acoustic tags (Tuohy et al. 2017). The preliminary results of 29 tagged Nassau grouper have confirmed that the presence of fish at the main aggregation site during spawning peaks was accompanied by higher than background courtship associated sound (CAS) that varied over time in response to the dynamics of the aggregation. Combined with closed-circuit rebreather dive surveys the abundance and size structure of the fish aggregated to spawn was collected efficiently, as sound levels were used to predict when most fish would be present at the FSA (Tuohy et al. 2017). Relationships between CAS levels and relative abundance of Nassau grouper at this site are still in development.

Spatial and temporal patterns of sounds produced by groupers aggregated to spawn collected in high resolution PAM studies have been used to confirm the specific area of habitat used as well as temporal patterns of fish reproduction (Mann et al. 2009, 2010; Schärer et al. 2012a, b; Locasio and Burton 2015; Rowell et al. 2012, 2015). Although the distance that low frequency sounds travel is limited (100 - 300 m), multiple instruments can be deployed in an array or acoustic detection can be conducted from surface platforms. For example, Rowell et al. (2010) detected areas of higher than background sound levels within the frequency band at which red hind produce sound by drifting on the surface with a submerged hydrophone at an FSA site west of Puerto Rico. Subsequent drift surveys by divers in the area confirmed that the concentrations of higher than background sound levels were at locations of high densities of red hind. Another method involved in-water floating drifters with hydrophones hanging 40 feet below a recording unit at the surface. The recordings made during this drift revealed CAS known to be produced by a variety of groupers that were correlated with geographical coordinates recorded by the unit's SPOT locator. This method allowed multiple units to cover a larger area simultaneously where CAS were detected as they drifted with the prevailing current. Finally, passive acoustic techniques have been successfully integrated into other platforms such as Slocum gliders (Wall et al. 2014) and wave gliders to detect CAS during FSAs in the US Caribbean (Chérubin et al. 2020). The advantage of these remote-controlled platforms is that they can provide real-time detections of CAS and can remain at sea long periods of time, including during unfavorable weather, and cover specific areas despite the currents.

In order to efficiently quantify the sounds produced by fish aggregated to spawn, a series of artificial learning techniques have been developed and tested on datasets recorded at known FSAs. Collecting PAM data at FSAs has become relatively simple with a variety of instruments designed for wildlife acoustic monitoring that can be programmed, deployed, and recovered over long periods of time (i.e. Loggerhead Instruments, Wildlife Acoustics). Research and development in this technology has made very small recording units that can be attached or inserted into the study animals (i.e. Open Tag accelerometer, Acousonde). Manual quantification and detection of fish sounds can be time consuming and prone to errors due to inconsistencies as well as the development of new results that require re-analysis of data. Automatic detectors applied to spectrograms have not been consistent in the detection of some sounds associated with FSAs since there are variations and overlap of other sounds in the marine environment that produce false positives. Algorithms that use artificial intelligence have developed in collaboration with computer engineering and signal detectors that led to the development of the fish acoustic detection algorithm research (FADAR; Ibrahim et al. 2018a, b, 2019).

A work still in progress in the FSA context is the quantification of individuals at an FSA at a given time using only PAM. In order to answer this key question, further research is needed in two main areas. First, the relationship between the amount of and type of sounds needs to be made, knowing the amount of fish present at any given time at the aggregation. This is complicated by the movement of fish through the area of the recording and may be investigated by installing wide listening arrays coupled with optical or sonar methods. Secondly, the proportion of fish producing sounds at a given time and place and their call rates (sounds/time) must be known. What has been observed to date is that this call rate is variable and influenced by both intrinsic (capability of a fish to produce sounds) and extrinsic (encounter rates with other fish may elicit different sound types depending on female or male interactions) factors. These two research questions need to be investigated at FSAs for species with different reproductive strategies and of different degrees of abundance to be able to progress with PAM for FSA in the stock assessment context.

C. Machine learning and automated analysis tools

William L. Michaels[1], Ryan Caillouet[2], Matthew Campbell[2]

[1]NOAA Fisheries Office of Science and Technology, Silver Spring, MD USA, [2]NOAA Southeast Fisheries Science Center, Pascagoula, MS USA

The implementation of cost-effective sensor and platform technologies to improve monitoring programs to help resolve data-limited fish assessments has been identified as a priority in the Gulf and Caribbean region, and there is an increasing interest to utilize cost-effective acoustic and optical systems to enhance data collections (Michaels et. al. 2019a). This is particularly true for improving FSA survey monitoring programs in remote areas. While these acoustic and optical sampling technologies provide more spatial-temporal resolution in the data collections to resolve uncertainties in fish stock assessments, there exists a significant problem of time intensive processes necessary to process large volumes of data in a timely manner for fisheries management decisions. This is particularly the case with imagery data from underwater camera and video surveys that are commonly used for fish abundance estimation. Recent advances in analytical tools such as machine learning (ML) provide automated detection and classification capabilities, and the use of ML tools can potentially reduce months of processing imagery data to days with reasonable accuracy. Some case studies that highlight the benefits of ML applications for marine and fisheries science are described in a recent report (Michaels et. al. 2019b). The most immediate benefit of utilizing ML tools is the ability to streamline data processing through automated detection and classification, while ML is also a powerful tool for assimilation of environmental data and predictive forecasting (Figure 13).

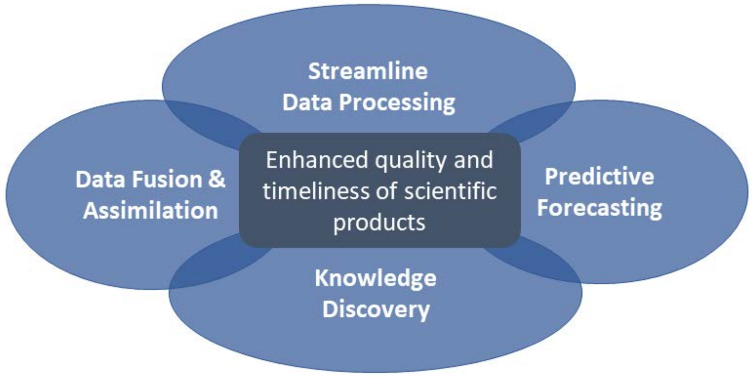


Figure 13. Given large data sets, unsupervised and supervised machine learning algorithms can provide benefits in reducing the costs of processing data, improvements in data assimilation, and predictive forecasting, which enhance the quality and timeliness of scientific products. Furthermore, increasing the accessibility of data for knowledge discovery using ML by the wider scientific community provides added value to the data enterprise.

ML algorithms have been available for decades; nevertheless, the application of ML has become more readily available in recent years because of the increase in data availability and increased computing power such as the general-purpose central and graphic processing capability of laptop computers. Furthermore, open source tools and cloud computing resources for ML have also become more readily available to the scientific community. For the purpose of this report, ML is defined as the discipline of computer science that enables computers to learn with algorithms and computational methods from data without predetermined equations and explicit instructions. For further introductory reading on ML, refer to Bishop (2006), Charniak (2018), Geron (2017), Kelleher et. al. (2015), Stone (2019), and Taulli (2019).

Learning approaches for ML computations can be categorized as unsupervised and supervised learning. Unsupervised learning uses the input dataset to train the ML algorithm, but the data does not contain information about the required output. The unsupervised learning is used to model probability densities of given input variables to discover hidden patterns or model the distribution of data. Some common algorithms used in unsupervised learning include cluster analysis, k-means, anomaly detection, neural networks, and principal component analysis. Supervised learning is the task of learning a function from labeled training data to achieve desired outputs, such as automated detection and classification. Supervised learning allows validation using a subset of the training data (Figure 14) and more rigorous statistical analysis (e.g., regression analysis, linear discriminant analysis, decision tree learning, support vector machines, k-nearest neighbor, backpropagation, Bayesian statistics, Kernel estimators, artificial neural networks) to evaluate model performance and bias (Russel and Norvig 2010; Bengio et al. 2013).

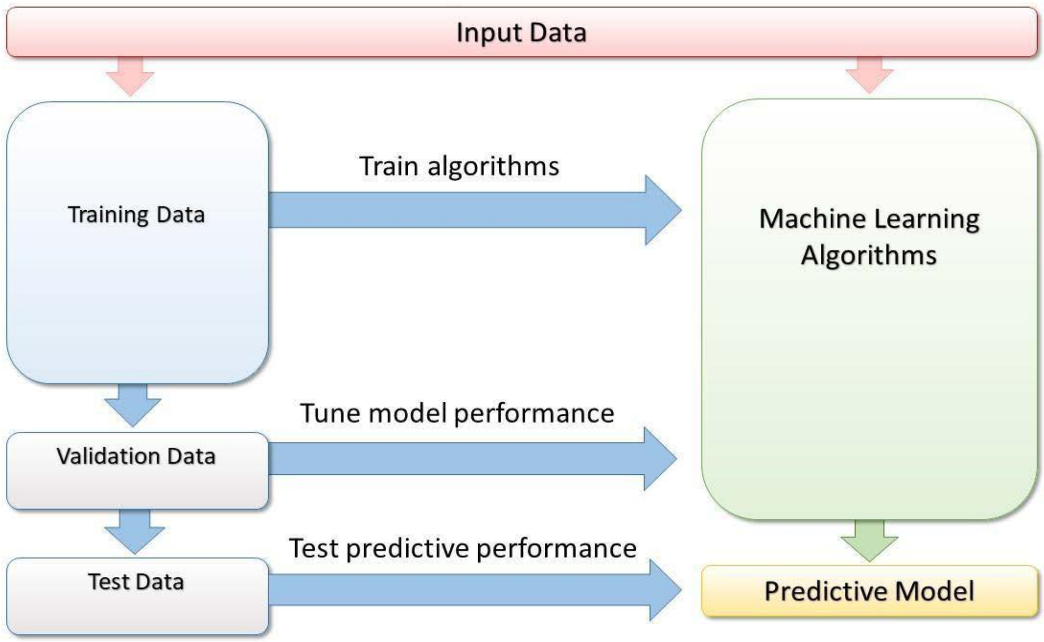


Figure 14. For supervised learning, labeled training data are used to train algorithms to achieve desired functions, such as automated detection and classification. A portion of the training data is used for independent validation and testing to determine the predictive performance and bias of the model.

Deep learning is a subset of ML algorithms with hierarchical learning that has received considerable attention in recent years (Stone 2019). The term "deep" is in reference to multi-layered neural network architecture, typically trained with labeled training datasets. In addition to neural networks, there are other categories of ML algorithms (e.g., nearest neighbor, naive Bayes, decision trees, linear regression, support vector machines). There are benefits and trade-offs of using neural networks and decision trees for fisheries science applications (Michaels et. al. 2019b). For example, the Random Forest method might be easier to interpret in regard to feature selection in comparison to the hidden layers of the neural network; however, decisions trees tend to overfit data and exaggerate minor fluctuations in data. The method referred to as pruning can be applied to remove unnecessary structure after construction by the Random Forests to minimize random error or noise of overfitting (Breiman 2001, Kong and Yu 2018). Ensemble-based modeling is another powerful approach that can combine ML algorithms to optimize model performance (Aggarwal 2018).

The open source tools and libraries of algorithms (e.g., Keras[3], TensorFlow[4]) have recently become more readily available to the wider scientific community for ML applications. Cloud computing resources for ML have also recently become available (e.g., Amazon AWS[5], Google Cloud[6], IBM Watson[7], Microsoft Azure[8]). For the purposes of this workshop, the open source toolbox named Video and Image Analytics for Marine Environments (VIAME[9]) is demonstrated to show the utility of integrating ML and computer vision into a user friendly end-to-end

[3] Keras, http://www.keras.io
[4] TensorFlow, https://www.tensorflow.org/
[5] Amazon AWS Sagemaker, https://aws.amazon.com/sagemaker/
[6] Google Cloud, https://cloud.google.com/ml-engine/
[7] IBM Watson, https://www.ibm.com/cloud/machine-learning
[8] Microsoft Azure, https://studio.azureml.net/
[9] VIAME, https://www.viametoolkit.org/

approach to address the need to streamline large volumes of imagery data collected from underwater fish surveys. NOAA Fisheries and Kitware Computer Vision Inc. worked collaboratively to develop the open source VIAME toolkit for the scientific community to streamline the post-processing of imagery data collected from fish surveys (Dawkins et. al. 2017; Richards et. al. 2019).

The VIAME software is an open source toolkit that provides a user-friendly end-to-end pipeline framework that uses advanced computer vision and ML algorithms for automated object detection, tracking, and classification (Figure 15). It is a flexible platform used for general detection and has been trained to detect fish in diverse ecosystems like coral reefs as well as benthic fauna and flora that make up coral reef habitats.

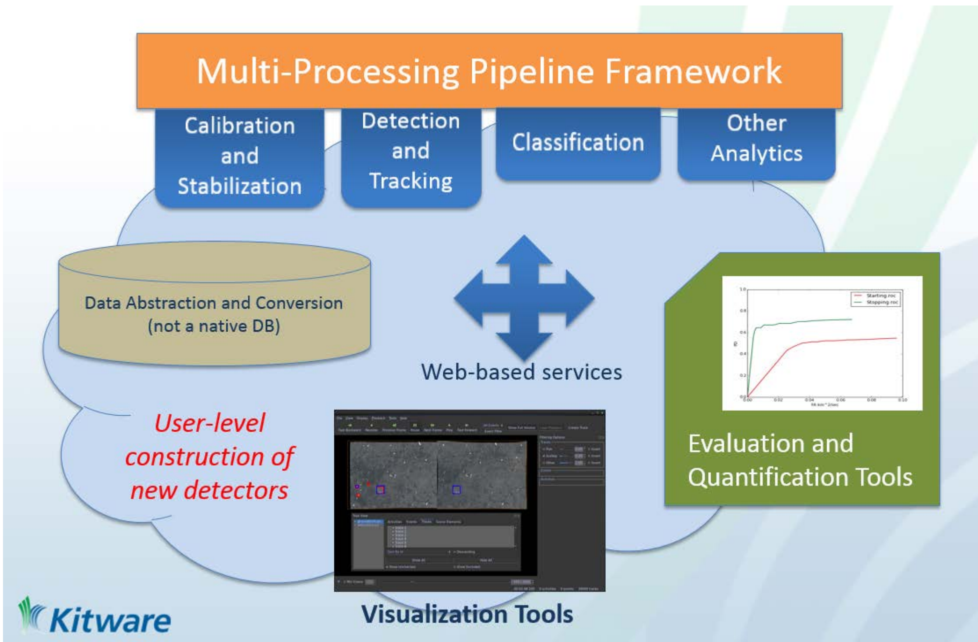


Figure 15. The open source Video and Image Analytics for Marine Environments (VIAME) toolkit provides an effective multi-processing workflow for automated object detection, tracking, and classification for a variety of applications for fisheries and marine science.

The NOAA Southeast Fisheries Science Center is using VIAME to develop automated detection and classification of reef fish to annotate the large data sets flowing from the SEAMAP Reef Fish Video Survey (SEAMAP-RFV) of the Gulf of Mexico. To date, individuals on the Mississippi Laboratories Reef Fish Unit have compiled 200 images for each of 40 managed species in the region. Images were annotated and processed using the deep learning method in VIAME and then evaluated for accuracy. Following the first trial we observed many inaccurate identifications and thereby decided to increase the number of images per species to 2000. Thus far we have only achieved that goal for a select few species (e.g. red snapper) and the new algorithms developed from the 2k image libraries performed very well for those select species (Figure 16). Given the success with the larger library, we are now compiling and annotating the images for the remaining species during the course of the standard annotation process. In addition, we have been in continuous contact with Matt Dawkins at Kitware on software upgrades, image libraries, and algorithm development. We hope to have a new version of the algorithm ready for trial for Spring 2020. Should the algorithm work well we will then begin to construct data set using automated processes for comparison to manual data annotations and for use in developing indices of abundance. Further down the line we will develop standard operating procedures to conduct workflow and supervised annotation of the automated process. Because the data from the video survey is critical for stock assessment, and most of the Gulf of Mexico assessments use a selectivity function, obtaining length data is critical. Since 2006 the SEAMAP-RFV survey has used stereo-cameras to obtain the critical length composition data. Similar to the abundance annotations, the measuring length of fish from stereo-video is a manual process. This is nearly as long of a process as the abundance annotations and thus there would be an enormous benefit to also be able to automatically calculate fish lengths.

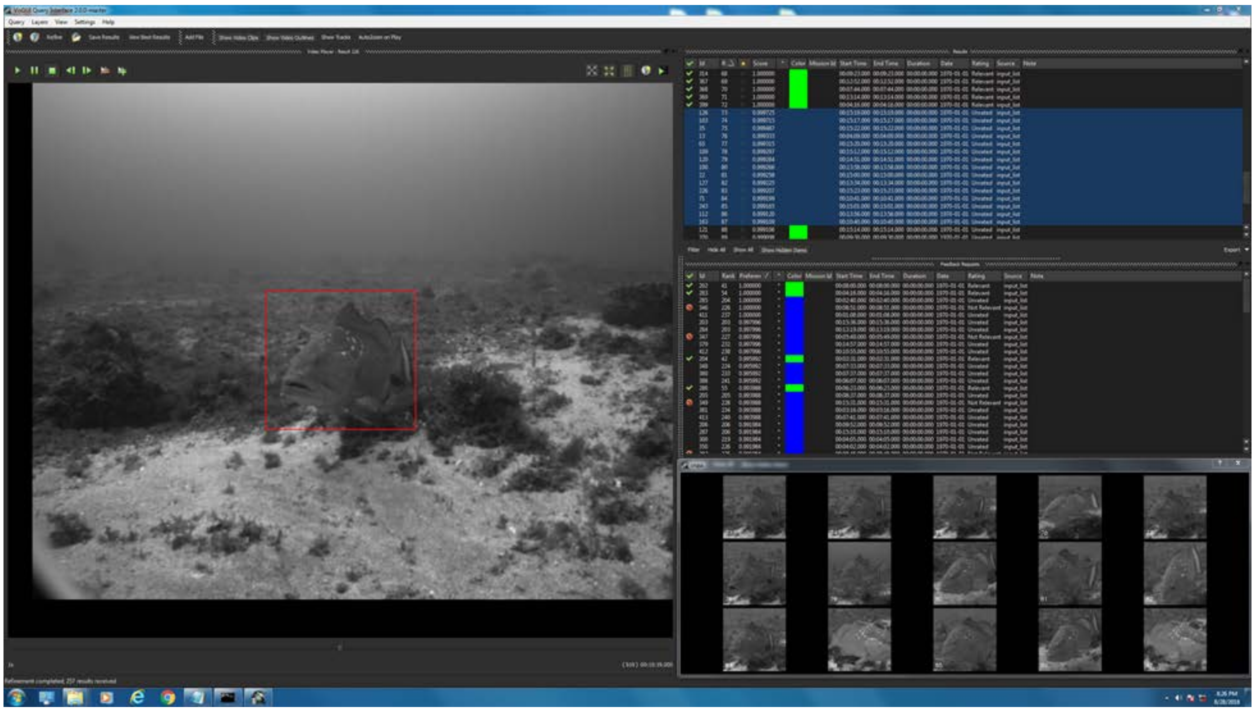


Figure 16. VIAME computer vision library and machine learning algorithms are utilized in graphical pipeline architecture for developing automated object detection and classification models in the marine environment.

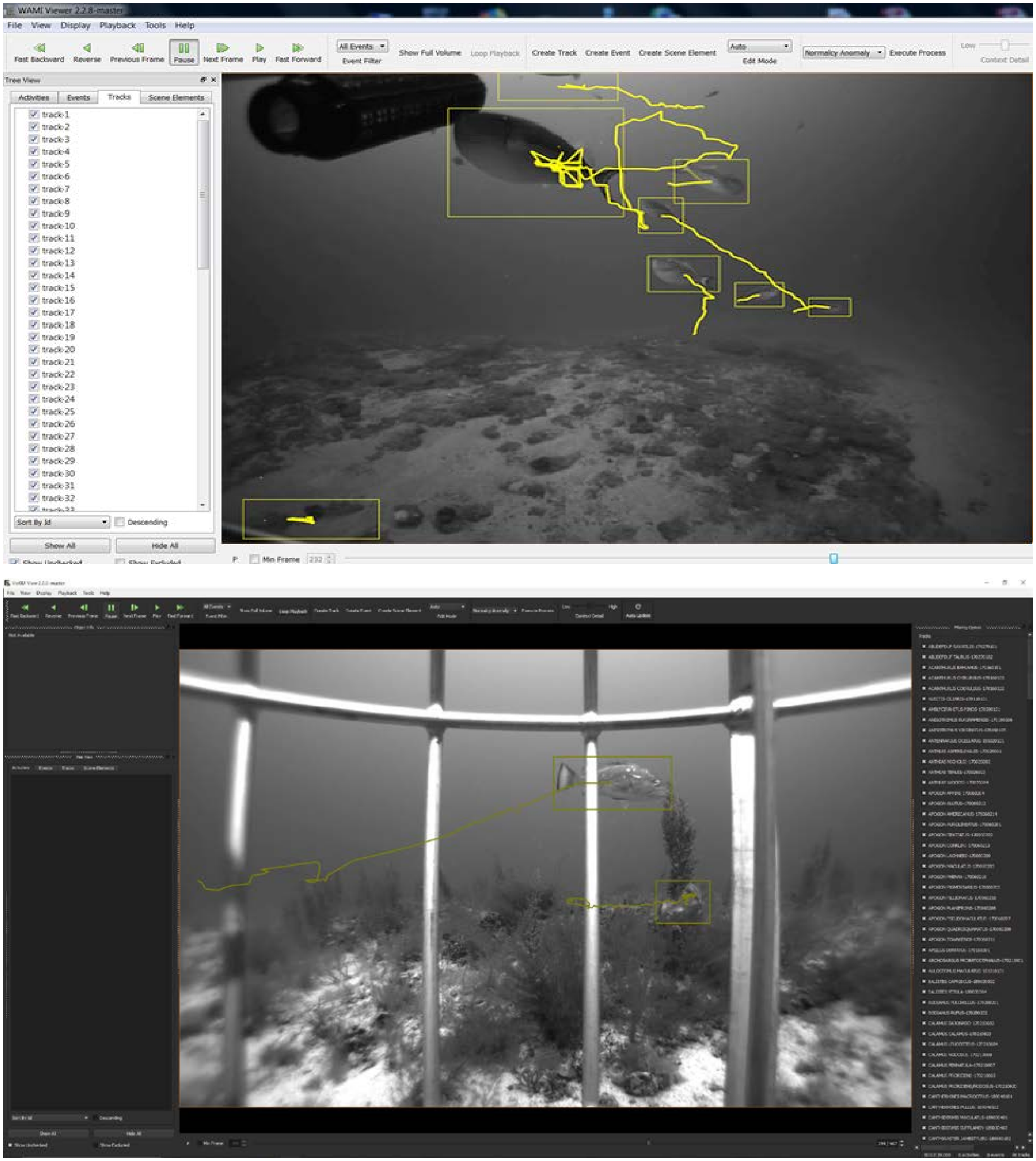


Figure 17. Two examples of VIAME computer vision library and machine learning algorithms are also used for tracking to minimize double-counting for improved abundance estimation.

The VIAME example provided by NOAA Southeast Fisheries Science Center highlights the potential benefits of ML to provide high quality and timely scientific information for fisheries management decisions. This case study emphasizes the importance of building image libraries of labeled training sets for reef fish species in the Gulf and Caribbean region. Ideally the libraries would be hosted and accessible online where many user groups can access and use them. While the automated image analysis effort in the SEFSC is in its early stages, it shows promise to resolve severe bottlenecks associated with annotation of large video data sets coupled with increasing demands on data timeliness. Thus far the effort has largely focused on critical species from the Gulf of Mexico and thus the developed algorithms are likely to be of limited use in the Atlantic and Caribbean basins where some species are held in common while others are endemic. In addition, there are some concerns that different light quality and or video quality could impact the precision of the derived algorithms and that need to be addressed. Thus, we recommend that interested parties begin to collate and annotate image sets with up to 2000 fish per species of interest. Those could be used by knowledgeable individuals to help produce basin/region-specific algorithms that could be supplied through user group forums. Ideally instead of work being conducted outside of potential users in any particular region, a workshop be held in which software developers could provide a quick primer lesson for interested parties. This would focus energy towards building the necessary image libraries in advance of the workshop that could then be used to provide a ready-made processing tool. Potentially, assuming timely delivery ahead of workshops, time could be spent evaluating precision from small image data sets collected prior to the workshop. Given scant resources but increasing demand for optics-based survey methods, demand will only increase and thus the time is ripe to begin exploring how this software can be utilized to help relieve identified bottlenecks. There has been considerably more interest in ML application in marine science, which can be attributed in part to the rapid development and availability of open source tools in ML analytics. As we proceed with supporting the implementation of ML, there is recognition that capabilities of ML analytics will continue to rapidly evolve in the coming years. A few general recommendations follow:

Develop and enable access to high-quality datasets: High quality data with enriched metadata is critical for developing reliable and accurate ML models for streamlined data processing, data assimilation, and forecast predictions. There was consensus on the importance of improving data accessibility for ML applications, including access to the wider community for research and knowledge discovery that provides added value to the data. Administrative policies are an important consideration, and some data may have confidentiality restrictions.

Model performance: The performance, error rates, and accuracy of the ML models must be documented and acceptable for the end user, and this requires labeled training datasets for training, validation, and independent testing of an algorithm. The reliability and credibility of the scientific products derived from ML are of paramount importance for its uptake and use.

Data enterprise modernization: There is a clear need to enhance data storage, accessibility, processing, and workflow capacity using open source tools and cloud computing when and where efficiencies can be gained. Hybrid solutions that integrate on-premise and cloud resources represent the vision for future improvements in data architecture. For successful migration to cloud computing, careful strategic planning must consider cost estimations, migration duration, administrative policies, need to minimize disruptions to workflow, and delivery of scientific products. Partnerships must be built toward shared objectives with an understanding of how ML will complement and augment human capabilities.

Address the big data bottleneck: Emerging technologies have resulted in a dramatic increase in the volume of data collected, which exceeds manual processing capacity; therefore, user-friendly ML toolkits are needed to reduce processing time and cost with automated detection and classification capabilities. While automated processes hold promise to alleviate processing bottlenecks, those processes will require significant supervision, QA/QC, and validation prior to full implementation. Without a high-quality QA/QC process, data analysis products will be highly vulnerable to scrutiny and could jeopardize their uptake and use, especially in stock assessments that have relatively high standards in this regard.

Promote collaborative ML research: In addition to improving ML algorithms and methods, open source tools that integrate ML and computer vision technologies into more user-friendly end-to-end pipeline workflow are needed. The community also needs to be engaged in the development of best practices, technical standards, and benchmarks to maintain the integrity of ML science. We advise the creation of user groups that can interact online and at workshops and meetings to meet various project objectives and goals and increase the utility of ML applications.

Partnerships: Trusting and sustained partnerships are built on three requirements: understanding the value-based drivers of each sector, leadership and careful planning, and commitment based on the significance of the collective goals.

Scientific exchange: Scientific exchange is critical to maintain knowledge about ML technology and is necessary to make improvements in the rapidly evolving ML discipline. Redundancy and duplication of effort is inevitable in a rapidly developing field but should nevertheless be minimized. Improvements in organization, communication, and collaboration are necessary to address the issue and a compelling example of this is highlighted in the U.S. and Norway exchange within this field; similar efforts should be encouraged for the GCFI community.

Training: Building and maintaining proficiency is a critical requirement for building ML capacity, and the best investment is to train your dedicated workforce. Scientists engaged in ML research will need more rigorous ML training, including a strong aptitude in statistical computations. Online introductory ML training would also be helpful to managers. Cooperative agreements and academic support to develop ML-focused training programs are also necessary to resolve the present shortage of ML experts and build our next generation of ML experts.

In conclusion, ML has already revolutionized how we will process and analyze scientific data. We are experiencing a turning point in data enterprise culture with how ML complements and augments how humans process and analyze data. The intent with these recommendations is to highlight some of the key requirements for advancing human-ML collaborations. The importance of partnerships is interconnected with each of these recommendations, and we hope this report helps the organizational culture shift to effectively utilize ML tools to deliver higher quality and more timely scientific products for policy decisions on the sustainability of ocean resources. In future GCFI workshops and across the Gulf and Caribbean region in general, we hope to energize the utilization of ML technology as the long-term benefits will reduce downstream costs associated with manual annotation of video data. For resource-limited regions, ML will improve the ability of laboratories in those regions to quickly and precisely produce useful datasets and analytical products for the management of natural resources.

VII. FSA Case Studies

Fish spawning aggregations have gained attention throughout the Caribbean region as communities recognize their importance in sustaining some of the most economically valuable fish stocks. As raised in the keynote presentations that kicked off the workshop, resource managers are engaging research experts, community stakeholders and citizen scientists in an attempt to establish collaborative research and monitoring approaches that address management and conservation objectives. Prior to the workshop, five FSA case studies were identified to form the basis of breakout group discussions on real-world science and management challenges. On the second day of the workshop, representatives from these five preselected FSA case studies described challenges and limitations for their target species or management area, including specifics such as remoteness of location, funding limitations, or varied levels of stakeholder participation. Participants in the workshop then rotated through the case studies in a consultative fashion; they served as a panel of experts proposing research and monitoring designs to address the management objectives outlined by the FSA representative. The approaches proposed considered possibilities given multiple future levels of resources and funding available. Following are the descriptions of each case study, with summaries of the group recommendations to address each respective challenge. The level of detail differed among case studies and related in many ways to what was already known about the FSA being discussed.

A. COBI Mexico

Cooperative of fishers involved in protecting FSAs in Mexico.

Case study:

Involving small-scale fishers as citizen scientists has proved key to achieving FSA site protection in the Mexican Caribbean, with five of eight known grouper and snapper spawning sites being protected since 2013 (Fulton et al. 2018). Challenges remain on methods to accurately measure the impacts of the conservation measures over time. Visual Underwater Census (UVC) have been conducted since 2013 during spawning periods to estimate abundance and size, but there is significant variability in the data (seasonal and weather variation, diver estimation variation due to large number of fish or site conditions). Hydrophones are also beginning to be installed at the most important FSA sites in an attempt to collect fish sound production data associated with spawning activity. The current UVC monitoring cost ranges from $1,000 to $2,000 a day, and low-cost methodologies that can be scaled at the regional level were discussed.

Group recommendations:

- Adding divers with laser calipers to the UVC monitoring, to improve site structure and recruitment estimates;
- Using stereo cameras and outsourcing analysis, or working with local universities through thesis projects or work experience;
- Implementing mark-recapture or mark-resight programs across the region (Mexico-Belize) to better understand regional fish migrations and movement.
- Improving species specific landings data for areas bordering the FSA sites (most landing data is binned by family in official statistics).

B. Black grouper in Bermuda

Case study:

The Black grouper is a large-bodied, slow-growing, protogynous hermaphrodite that is known to aggregate to spawn, and population genetics indicate that the Bermuda population of this species has low connectivity with other areas and so must be managed conservatively. In addition to a complete ban on the use of fish traps that has been in place since 1990, the Government of Bermuda has enacted a suite of regulations to manage the local Black grouper fishery, but there is a lack of information on population status and trends. This case study examined the potential for using technology applied at the two known Black grouper FSAs as a way to monitor the population.

To help constrain the catch of Black grouper, there is a bag limit of one fish per vessel per day across all fishery sectors, which has been in place since 1996. The commercial fishery reports catching an average of 775 (range 600-1200) Black groupers each year, but this is self-reported data and, because of the need to appear compliant with the bag limit, almost certainly a significant underestimate. However, with Bermuda's highly dispersed landing sites and lack of a central processing facility, catch validation and sampling is challenging and resource intensive. Given their size, Black grouper are difficult to catch using a pole spear, but a small number of licensed recreational spear fishers report catching an average of 7 individuals per year. The extent of recreational catch using hook and line is unknown.

A minimum size limit for retention of Black grouper was set at 75 cm fork length in 1996. This was increased to 95 cm FL in 2010, in response to a new deep trolling technique that disproportionately caught females in the 75 – 95 cm FL size range. This large minimum size now truncates any size frequency distribution data that can be collected from the commercial fishery. Further, the use of reported weights for size frequency analysis over time is confounded by these changes in the minimum size. Age and growth work determined that sexual transition occurs when individuals are 110 - 120 cm FL and 10 - 15 years of age, with males then typically surviving a further 10 - 15 years. However, this is a period of asymptotic growth, with fish gaining only a further 30 cm in length, and size is not closely tied to age after transition.

There are two known Black grouper FSAs, located off the eastern and western ends of Bermuda. The western site is located near a Red hind FSA so, even though the Black grouper FSA was not known to managers until 2010, the area had been closed to fishing from May through August each year since the 1970s. The eastern site was reported to managers in 2004 and was closed to fishing from May through August beginning in 2005 (Figure 18).

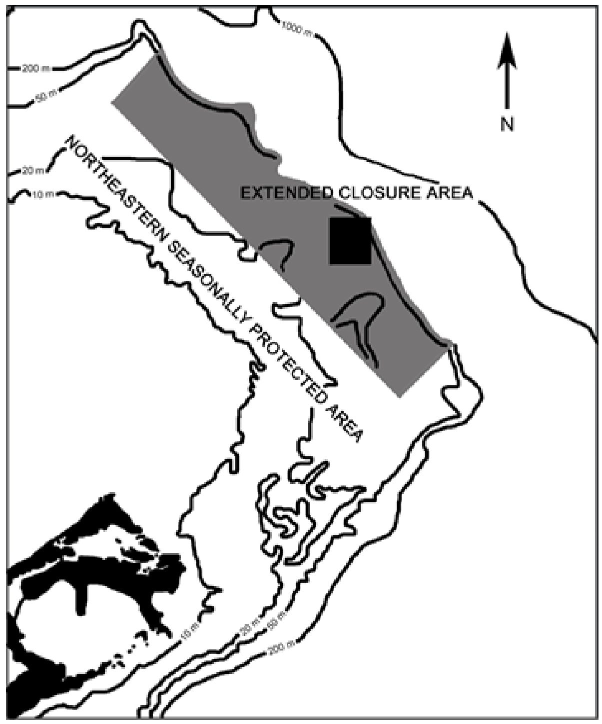


Figure 18. Location of the area managed for the protection of the Black grouper FSA in Bermuda.

Acoustic tagging data from the FSAs indicate a protracted spawning season, with numbers of tagged fish visiting the site monthly from April through November. The eastern site has therefore been closed to fishing through the end of November since 2008, and the same regulation was applied to the western site when managers became aware of it in 2010. The beginning of the seasonal closure period was moved forward to April 15 starting in 2017. Nonetheless, catch of Black grouper is allowed during the reproductive season outside of the two seasonal closure areas where the FSAs occur.

A better understanding of population status and trends is needed to determine the feasibility of adapting management while maintaining a sustainable Black grouper fishery. One of the goals is to determine an appropriate level of total allowable catch, and possibly implement individual catch quotas. This could then allow a slightly greater daily bag limit for commercial fishers in order to increase the efficiency and profitability of their fishing. This should also reduce the incentive to under-report catch and make sampling of the landed catch more cost-effective. However, Black grouper occur at low densities outside of FSAs, and there is no fishery independent monitoring taking place at this time.

Research at the eastern FSA site described the temporal dynamics and behavior of aggregating Black groupers (Luckhurst 2010) and determined residency patterns via acoustic tagging. With sexual transition known to occur over a narrow size range (110 – 120 cm FL), fish can be sexed visually based on estimated length, and sex ratios at the FSAs can determined based on size structure.

Each month during the spawning season, starting around the full moon, male Black groupers form a dense aggregation in the water column above the reef and produce audible sounds

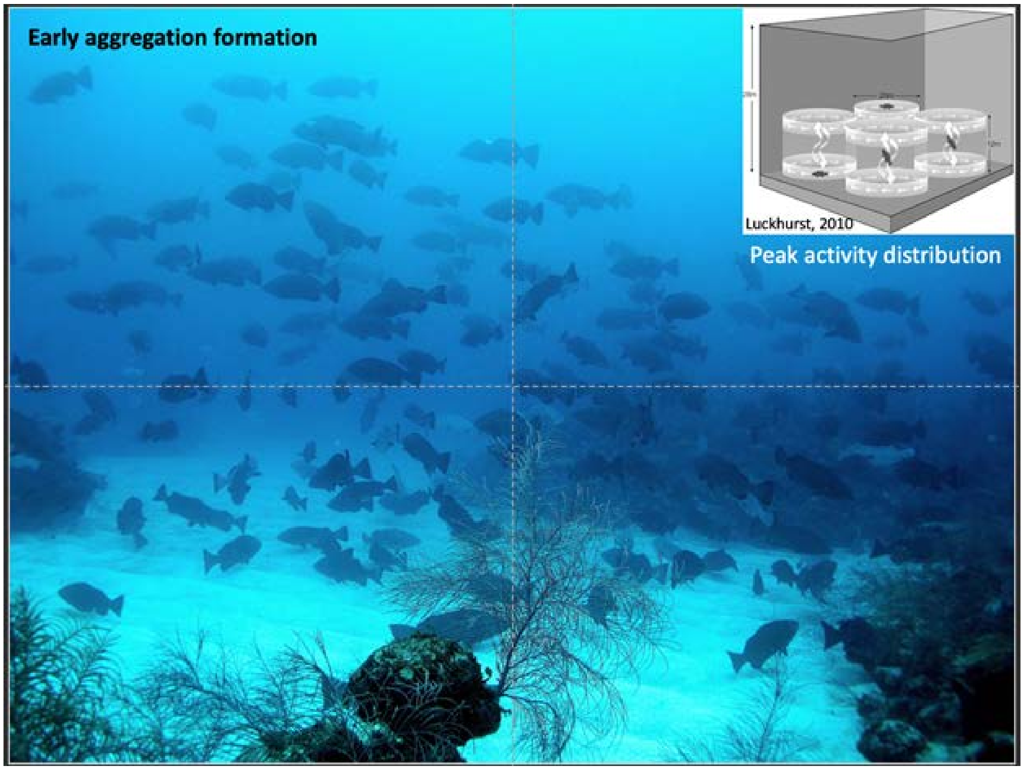


Figure 19. Aggregation of male Black grouper at the Bermuda FSA.

(Figure 19 - main photo). Females arrive at the site just before the third quarter, and males and females then spread out over a larger area in lek-like territories (Figure 16 inset), with 6 – 10 females associated with each male. Abundance peaks just after the third quarter, with spawning presumed to occur at this time based on observations of smaller fish with distended abdomens and capture of a female with hydrated eggs. The aggregation then dissipates by the new moon.

Two management-related questions were presented and discussed to guide potential projects using new technologies. The first question concerned how to evaluate the abundance of Black groupers that aggregate to spawn in order to develop an index based on FSA monitoring that could be used to evaluate the stock. Secondly, finding a way to document the size-structure of individuals at the FSA would allow the sex ratio to be determined, a useful metric to monitor, and would also contribute to a broader evaluation of the stock.

Several characteristics of the aggregation sites have proven a considerable challenge to research efforts, including the distance from shore and prevailing sea conditions on the platform edge, as well as the depth of the sites (33 m / 110’). This is further complicated by limited access to suitable research vessels, a lack of technical diving capacity, and limited resources overall. In addition, acoustic tagging efforts are challenging because of barotrauma impacts. A seasonal thermocline forms at these sites, but a positive feature is that visibility near the bottom is generally good and facilitates relatively clear photos and video.

Group recommendations:

- Include active acoustics (echosounders) surveys to assess males present as females generally remain too close to the seafloor to be detected using acoustics. A relative index could be developed that assumes a sex ratio. Acoustic surveys can be conducted from boat or AUV.
- Low-tech sonar could be used to create a habitat map to determine particular features that attract fish or that influence currents in the area. Habitat types are also necessary to quantify extent of benthic habitats used by groupers. Repeated surveys could detect shifts or expansions/contractions in the area utilized due to increased/decreased numbers of fish at the FSA.
- Active acoustic methods are time-sensitive, as they need to account for the range of sex-specific behaviors at different stages during the formation of the aggregation. Further observations are needed to confirm that the timing of these behaviors relative to the moon phase is consistent, and behavior must be monitored visually in conjunction with the acoustic surveys to confirm whether the males are aggregated or distributed across their territories. Understanding these patterns is key to conducting acoustic surveys at the appropriate time and then calibrating the resulting data.
- Suggestion for determining both the number and size frequency distribution of Black grouper at the FSA would be a tag and recapture or re-sighting survey to measure changes in abundance at over time. These surveys would have to be conducted by technical divers with either mixed gas or closed-circuit rebreathers. Repeated dives would be necessary to collect the appropriate information and to evaluate changes in size and abundance. This was not a preferred option given the lack of technical diving capacity in Bermuda and the low probability of being able to conduct subsequent dives at the FSA site over time.
- Remote optical technology on towed or drop rigs was also suggested as a means of enumerating fish at the FSA, and incorporating stereo-cameras or calibrated lasers to measure fish would provide length frequency distributions. These methods could provide valuable confirmation of fish behavior and size-frequency distributions to corroborate and calibrate active acoustic surveys. However, the logistical constraints of conducting repeated video surveys at the FSA are significant and this approach on its own may not generate sufficient quality data over time.
- Finally, the use of passive acoustic receivers to monitor the courtship-associated sounds known to be produced by Black grouper was recommended. Some passive acoustic data have been collected at the western FSA site, but have not yet been analyzed due to a lack of resources. Understanding the variability in call rates of individuals and the sex-specific sources of sounds is key to be able to use passive acoustic monitoring to monitor the abundance of fish at the FSA. Some visual calibration of passive acoustic data is therefore deemed necessary.

C. Florida Keys multispecies aggregation sites

Case study:

The Florida Fish and Wildlife Commission and their partners have been conducting research on spawning aggregations in the region for ~10 years. After successful management was demonstrated from spatial closures provided by a network of no-take marine reserves in the Dry Tortugas, other locations were evaluated for their potential importance as either single- or multi-species aggregation sites. One location that was well known as a mutton snapper and potentially a multi-species FSA was the Western Dry Rocks reef (Figure 20). Various approaches have been used to evaluate this location with limited success. One of the issues preventing collection of data was how heavily utilized the area was (Figure 21). This led to fisher/diver conflicts, equipment tampering, and threats to fishermen cooperating with scientists. Because the fishery is lucrative, management can be contentious with the community members. Community outreach and opportunities to interact to discuss the Western Dry Rocks FSA have largely been unsuccessful as fisherman rarely participate and when they have, the science itself has largely been questioned. For instance, fisherman dispute that black grouper spawn in the winter months, despite ample data indicating the temporal trend specifically for this location. We focused on two primary questions during the discussion session: 1) how to better improve the science, and 2) how community engagement can be improved.

Figure 20. Location of region roughly called 'Western Dry Rocks' in the box inset with Key West labeled in the upper right corner of the map. Points on the map represent locations of telemetry receivers.

Group recommendations:

1) How to better improve the science

- There was some discussion that extant datasets regarding histology were not perhaps being accessed and could be pulled in to provide some clarity, specifically for providing information on black grouper spawning in the region.
- There is an active and passive listening array that has recently been set up throughout Western Dry Rocks that is beginning to provide data streams on noise production.

Preliminary data has picked up black grouper sound production at the Western Dry Rocks location.

- Ichthyoplankton tows could be a low-cost method for demonstrating that Western Dry Rocks is a multi-species aggregation site.
- Have a third-party independent review of the science to determine if it is valid to call the area a multi-species aggregation site. This will keep the science more neutral in the eyes of the community.

Figure 21. Photograph taken during an aerial survey of boats fishing at Western Dry Rocks during the full moon of May 2011 which is a known time for mutton snapper to aggregate to spawn.

2) How to improve community engagement

- It was suggested that a third party to act as an intermediary and facilitate interaction between regulatory agencies and the fisherman. One example given was the Sea Grant Extension Program.
- Bring fishers from other regions of the Caribbean to interact with Florida Keys fisherman. Have examples of fishers that can speak to what happened when there was no FSA management and when there was FSA management.
- It was suggested that a public relations media campaign aimed at engaging the clientele coming to the Florida Keys that support the charter fishery operating in the region might help. This could provide the public with a better understanding of why proper FSA management could create sustainable fisheries that will help generations to come to enjoy the fishery.

D. Palau snapper FSA and population impacts

Case study:

Our research questions were associated with a spawning aggregation site for the twin-spot red snapper (*Lutjanus bohar*) that have been studied for over a decade in Palau. The aggregation site occurs at Shark City, which is a well-known dive site off the western barrier reef of Palau. Red Snapper aggregate to spawn there every month of the year with the aggregating and spawning activity all occurring over a 7-9 day period during the week leading up to the full moon. The behavioral dynamics and environmental conditions at the site are highly conducive for quantitative studies of the spatio-temporal dynamics of spawning. Briefly, through monitoring this aggregation continuously and throughout the year for so many years, we've learned that the timing and location of the behaviors are reliable and predictable, which has allowed us to begin to monitor (count) fine-scale changes in the abundance of fish at the entire aggregation as well as overall spawning activity.

The focus of this research is not on this particular aggregation, assessing trends in the size of the aggregation or the larger regional population over time, or anything related directly to localized management or conservation of this species in Palau. Rather, we are attempting to take advantage of the uniquely “convenient” behavioral dynamics of this aggregation to answer broader, theoretical questions about the relationship between fish abundance and reproductive activity and output. Specifically, we are interested testing for evidence of mating system Allee Effects in fish spawning aggregations, a phenomenon also referred to as depensation in the context of fisheries science. This theory predicts a positive, density-dependent relationship between the density or abundance of reproductively active individuals and the per capita reproductive rate or total reproductive output of the breeding aggregation. For animals that have evolved to reproduce within large aggregations, reproductive development (e.g. egg maturation and ovulation) and activity (e.g. courtship behaviors, color changes, spawning rushes) of individuals are stimulated by the presence of conspecifics such that reproductive activity and output increases disproportionately with increasing numbers of conspecifics or the overall density of breeding individuals within an aggregation. This behavior holds serious implications for conservation and management, because it suggests that a minimum threshold of breeding individuals (or a minimum aggregation density) is needed to produce positive population growth, and breeding activity can decrease substantially or even cease altogether below a certain aggregation size or density level. Empirical evidence of mating Allee Effects (a type of component Allee Effect) has been demonstrated for numerous gregarious species of animals, including marine invertebrates. While it is perceived that fishes that form transient spawning aggregations are thought to also demonstrate this effect, and anecdotal evidence has been reported for a few species, there is a lack of empirical evidence to support the theory.

For the past five years, we have been using expert diver counts (i.e. those of us with extensive experience with the aggregation and underwater visual censuses of reef fishes) to census the daily total abundance of fish present at the aggregation, the number of spawning rushes per daily spawning period, and the duration of the spawning period each day. Since fish spawn every day of the aggregation period, we simply plot the relationship between fish abundance and both spawning activity (via number of spawning rushes) and spawning duration (number of minutes from first to last spawn). Thus far, our preliminary results show an exponential relationship between fish abundance at the aggregation site and spawning activity, which supports the existence of mating Allee effects. However, given the biases and limitations of visual estimates of fish abundance, we sought out the feedback and suggestions from workshop participants for alternative methods to improve the accuracy, precision, and replicability of our study. In addition, we posed two additional questions regarding other potentially important avenues of research and approaches for assessing the impact of diver ecotourism on spawning activity.

Questions Posed to Participants:

1. *Given the predictability and convenience of the mating system of the red snapper in Palau for gathering quantitative information on spatio-temporal dynamics of spawning behavior, what approaches and tools could be useful for improving the precision and accuracy of estimates of the relationship between fish abundance and spawning activity?*
2. *Diver tourism has recently surged at the site with large numbers (100+) of recreational divers present at the site during spawning within peak spawning days. What approaches*

and tools could be used to quantify the impacts of diver disturbances on spawning activity?

3. *Given the first two questions, and the opportunity to use this site to improve our understanding of a relatively pristine (unfished) spawning aggregation, what are the most important study questions to answer next from a scientific, management, or conservation perspective?*

Group recommendations:

1. Testing for Allee effects
    - Side-looking multibeam sonar could be used to estimate school volumes (fish distributions) and compare this metric with spawning activity.
    - A moored optic-acoustic system would be ideal for the system, because it would allow continuous monitoring of fish abundance and activity at the site, assuming it was positioned properly; consider reviewing results and approaches covered in the 2018 workshop on optic-acoustic technologies.
    - An upward or sideward looking lander with wide band, active acoustics would allow for generating estimates of fish density and school volume over time.
    - If gear cannot be permanently deployed, continue using boats, and conduct boat-based acoustic surveys to generate estimates of school volume, packing density, and fish abundance over time and space.
    - Acoustic data and stereo video data would be critical for validating and generating a correction factor for the diver censuses to generate a more precise, accurate, and replicable approach of estimating total fish abundance per day.
    - Validate the use of spawning rushes as a proxy for spawning activity by comparing the number of rushes in which no gametes were released, only males released, and both males and females released gametes. Spawning rushes can be tracked using acoustic telemetry with encoded pressure and accelerometer data.
    - Video surveys of spawning activity are needed to compare with diver counts of spawning to validate and correct for diver bias in spawning activity estimates.
    - Examine whether fertilization rates vary with spawning group size, aggregation size, and other metrics, as it would increase accuracy of estimated reproductive output in relation to these factors.
    - Consider active acoustics using high-frequency transducers to survey the backscatter of gametes (eggs) to estimate their volume and density; this could be a more direct, informative estimate of how reproductive output changes in relation to aggregation size or fish abundance/density.
    - Consider measuring the packing density of fish within the pre-spawning aggregation (i.e. when all fish coalesce in a tight ‘tornado’ prior to spawn) as the metric to compare with reproductive activity, because it may be a more relevant driver of activity. That is, perhaps it’s the tight spacing of fish prior and during this time (rather than simply the # of fish in that tornado) that “excites” the fish and stimulates them to spawn.
    - To ensure this relationship is consistent and not unique just to this one site, it is important to sample a low-density, low-abundance site to test whether this same relationship holds up.

- Comparison of multiple sites would also improve confidence and quality of these results as a true pattern.
- Mark-resight approach could be used to improve accuracy of fish aggregation size; however, the protocol needs to consider the behavior of the fish to assess and minimize bias. For example, if you tagged 50 in the afternoon and then attempted to re-sight the next morning during the pre-spawning tornado, it's possible that all the tagged fish are hidden in the middle and would not be re-sited. Conversely, perhaps tagging and re-sighting during the post-spawning time would be more reasonable with lower bias.
- Stereo-video surveys would improve estimates of 3-D school volumes and packing density and provide information on length-structure in relation to active acoustics to generate estimates of fish abundance from school volumes (via comparisons of target strength distributions and length distributions).
- Ideally, simultaneous stereo-video surveys from above and laterally would provide the most robust estimates of school volume and fish packing density; perhaps even use this approach for estimating nearest neighbor distance as a proxy for the effect on density/abundance on spawning.
- If females can be identified and distinguished from males within the aggregation, consider focusing mainly on monitoring and censusing them only, as it may be the density or abundance of females that drives changes in spawning activity rather than total fish abundance; this metric may be particularly important if sex ratios deviate from 1 to 1 within the aggregation or if sex ratios change daily during the total, weeklong aggregation period.
- Consider machine learning (and collection of many images each survey period) to increase speed of data processing over time and reduce human/observer bias in estimates of fish abundance, density, etc.

2. Impacts of diver presence on spawning activity

- Active acoustic surveys and monitoring could generate estimates on the volume, density, and area of bubbles created by divers to compare with spawning activity and behavior to assess impacts.
- Passive acoustic monitoring of ambient noise could be used in conjunction with diver surveys, active acoustics, stereo video, and other approaches to compare diver and boat-generated noise with fish abundance, distribution, density, and spawning activity.
- Consider not just the pure number of divers in relation to spawning activity but also how groups of divers behave and the effects on spawning. For example, disturbance and impacts are likely high when divers swim into or chase the school but low or insignificant when divers remain on bottom, away from the school.

3. Other important research avenues

- To improve understanding of regional population, you could use telemetry (acoustic tagging) and traditional tagging to understand movement patterns, residence time, and possibly the distribution of FSAs in relation to home sites around Palau. These tools would also improve understanding of catchment areas in relation to spawning areas.
- Recruitment studies are needed to understand and evaluate how changes in spawning activity may scale up to population-level effects; This could be tracked by direct surveys and monitoring of larvae/YOY/juveniles over time (years).

- Stereo video surveys and monitoring over time could identify recruitment (fishery) patterns and new recruits into the adult population through changes in length distribution of fishes at the spawning site.
- Mark-resight studies of fish at the FSA could be used to increase understanding of aggregation size and possibly total population size (if different fish are coming to the site from different home sites during the year). Telemetry would be helpful to validate the results of mark-resight work to explore whether the same fish always come back to the same site or different fish come to spawn at the site each month.
- To monitor impacts of fishing and the status of the aggregation over time, you need to monitor and census the aggregation every year and monitor changes in length distribution of the fish as well.
- Given the number of dive operators and companies diving daily around Palau, connecting with them could help generate anecdotal observational data on the movement of fish to and from the spawning site and possibly the identification of new spawning sites.

E. Trinidad Atlantic Goliath grouper and Hammerhead shark aggregations

Case study:

The island nation of Trinidad and Tobago has several challenges in managing their marine ecosystems. There are limited data on the status of fish stocks, made worse in some ways because data that is collected on catches by the Fisheries Division is aggregated into groups like "grouper" (all grouper species), "redfish" (snappers), and "sharks". The fisheries primarily operate trawls, surface gillnets and hook-and-line at the artisanal level in local waters. Laws that govern the catches of fishes were established in 1916, have not been updated since, and are minimally enforced, resulting in an open access situation (MAGLA 2015). The coastal waters around Trinidad are challenging to survey independent of the fisheries due to typically poor water clarity. Very little seabed habitat mapping has been conducted in the region. Two areas of interest were identified related to aggregations of fishes, and panel members were asked to provide suggestions for new observational methods that would provide insights into habitat use by two key species that aggregate in Trinidad.

Oil rig in northwest Gulf of Paria, Trinidad

Topic 1: Goliath Grouper spawning habitats around oil and gas platforms

Atlantic Goliath grouper (*Epinephelus itajara*) are caught as part of the grouper fishery but because they are not identified when reported at the dock, there is no time series of catch that could lead to an understanding of status in the stock. Juvenile fish are seen in some estuarine habitats, e.g. mangrove swamps, as well as suspected to occupy some of the numerous offshore oil and gas platforms. Atlantic Goliath grouper are known to occupy artificial habitats such as oil rigs and artificial reefs as large juveniles, adults, and during spawning aggregations in other regions (Gerhandinger et al. 2006, Giglio et al. 2016, Koenig et al. 2011). Shell Oil has conducted multiple remotely operated vehicle (ROV) video surveys of platforms around Trinidad that may provide an opportunity to observe Goliath groupers and other fishery species utilizing the structures. These are being provided to Dr. Kingon for research purposes. Unfortunately, access to the platforms themselves is currently restricted by a 500m radius no entry zone. The participants were asked:

What cost effective methods could be used to survey Goliaths toward the goal of understanding the status of the species and fishery?

Group recommendation:


A juvenile Atlantic Goliath grouper caught, tagged and released in the Caroni Swamp, Trinidad.

- Participants suggested a range of approaches to better sample Goliath grouper, recognizing limited resources. The lowest cost effort identified was to identify cooperative fishers who would report the species when caught, where and when it was caught, and possibly provide biological samples; a method currently being implemented but that requires expansion to include more fishers. Exploration of the ROV videos would be the best first pass at developing a video or acoustic survey of the platforms for Goliaths, however the quantity of videos provided by Shell Oil are daunting and so automated image analysis methods would be the most effective method for screening the videos for Goliaths and other species.
- Free video viewing software like VLC and SM Viewer (https://www.videolan.org/vlc/index.html, https://www.smplayer.info/) could be used to select a few clips of video that contain Goliaths and other species of interest. The sound files, if they exist, could also be saved separately from the video data to quickly scan for acoustic signatures typical of Goliath groupers. Free machine learning methods like VIAME (https://www.viametoolkit.org/) could be used to set up a detection library to detect objects (fishes) in the numerous videos, narrowing the video frames that need to be viewed and validated by an analyst. An iterative process using these machine learning techniques could be used to quickly improve the analysis process and to obtain the data of interest.
- Following confirmation that Goliath groupers are using the platforms, the oil companies could be engaged to assist with deploying sensors on the platforms for an independent survey that could provide indicators of abundance to track status of the population. The most popular sensors suggested were passive acoustic recorders since Goliaths are known to produce sounds especially during courtship and spawning and to defend their territory. Fortunately, the sounds produced by Goliaths are well characterized and a relatively rapid analysis of the passive acoustic data could be conducted using automated detection algorithms. One challenge using passive sound recorders around platforms would be the background noise from platform operations, some of which could be overcome through data filtering.

- Active acoustic sensors such as split beam echosounders and imaging sonars (e.g., DIDSON) could be used to survey the platforms from vessels (where oil companies would allow close access) or attached to platforms that Goliaths occupy. Analysis of the acoustic data could produce detections of large targets that would likely be Goliaths, but some form of visual validation using drop cameras would still be required to assign and enumerate targets and estimate numbers of Goliaths.

Topic 2: Hammerhead sharks aggregate at pupping grounds

Hammerhead sharks, primarily scalloped hammerheads (*Sphyrna lewini*), are caught by surface set gillnets in high abundances from December to April along the north coast of Trinidad in waters about 30-130 ft deep. Primarily juveniles are landed and sold at markets to supply the popular local dish “Bake and Shark”. Landings are recorded as “shark” and sometimes “hammerheads”, but Trinidad has 7 species of *Sphyrna*, and none are identified to species by the Fisheries Division. The current high catch rates are likely unsustainable and risk depleting the population. A time and/or space closure especially for certain gear types like gill nets could be proposed, but the extent of the pupping ground is not well defined. Participants were asked:

Bake and shark is a popular regional dish in Trinidad and Tobago

What type of survey program could be developed to define the habitat region for scalloped hammerhead sharks?

- **Group recommendation:** Panel members suggested a first step to engage fishers to sample catch for fishery dependent data for biological samples and catch rates.
- Cooperating fishers could carry inexpensive GPS loggers on their boats to determine the spatial distribution of effort.
- A fishery-independent gillnet survey (or other fishing method that is effective but with lower mortality) could be established to produce indices of abundance for the target species. Aerial surveys could collect information on fishing boat distribution to delineate possible habitat area for the sharks, though it was noted that many of the gillnets are set at night, making such observations difficult.
- Aerial surveys to detect sharks near the surface would be challenging due to high water turbidity and the likelihood that sharks will most often be near the surface at night for feeding and likely resting near the seabed during the day. Preliminary stomach content data suggests they are eating deep water fishes that likely vertically migrate as well.
- Establishing an array of acoustic receivers and tagging sharks may be possible, though fishery catch of tagged sharks could be very high with risk of non-reporting and lost tag data. We learned of acoustic release devices that would make deploying and retrieving acoustic telemetry receivers much easier in this environment that experiences high wave action, high turbidity and is relatively deep (often >100 ft). Explanted or implanted acoustic telemetry tags would be able to record temperature and depth but would need to be recovered to process data. A cabled telemetry receiver integrated with another observatory platform could provide real-time detection that would indicate timing of

arrival of the sharks and inform possible time-closures for protection. The feasibility of capturing and tagging mature females would require further exploration.

- Satellite tags are a more expensive option (about $5000 per tag) but would not require the array of telemetry receivers. Satellite tags also log depth and temperature data to understand movement between deep and shallow habitats on the shelf. Fishers could be employed to attach tags to sharks although they would have to modify their fishing methods as the gill nets are soaked for many hours and nearly all hammerheads caught are dead upon net retrieval.

Juvenile scalloped hammerheads seen at Guayaguayare Fishing Depot, Trinidad taken by Adrian Wilson.

VIII. Concluding Workshop Plenary

A final workshop plenary was given by Dr. Will Heyman who provided an overview of existing cooperative monitoring programs and shared his personal thoughts for ways forward to grow additional networks of experts toward monitoring FSAs throughout the Caribbean and Gulf region.

Furthering cooperative monitoring programs

William Heyman

LGL Ecological Research Associates, Bryan, TX USA

This workshop has allowed participants an overview of a wide variety of available techniques and methods for monitoring and assessing fish spawning aggregations. This brief section attempts to remind readers of this workshop report of the Caribbean context and offer thoughts on the way forward. The Gulf and Caribbean region includes a wide variety of nations and territories, cultures, cuisines, and languages. We also share marine resources that are connected by larval and adult migration, ocean currents, genetics, and markets. We all depend on these resources and have shared and collective responsibility for their sustainable management.

Nonetheless, the region is characterized by small scale fisheries and a general paucity in resources and capacity for governance. While advanced technologies have become available and are becoming more widely used throughout the region, FSA sites and their associated fish populations continue to decline in large part from a lack of monitoring and enforcement. For example, Nassau grouper's natural range transcends 43 nations or jurisdictions and with a few notable exceptions, FSAs continue to be overfished and otherwise extirpated and the regional population remains critically threatened, according to recent assessments of the IUCN (Figure 22).

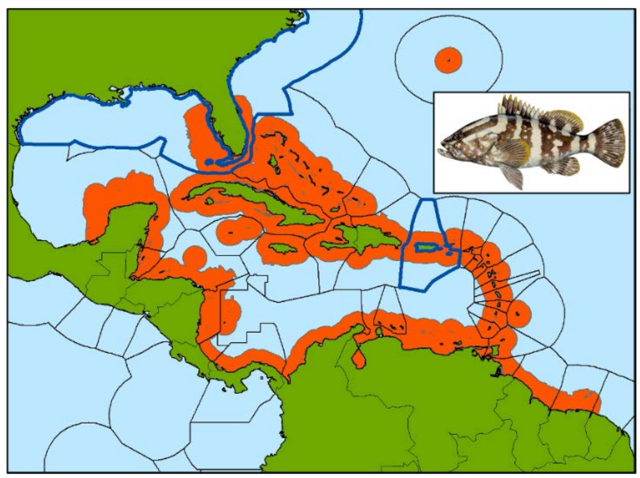


Figure 22. Nassau grouper has an extant geographic range that transcends jurisdictions of 43 nations or territories (range extent data from IUCN).

To sustain productive fisheries will require coordination between top-down (e.g. national and regional fisheries management and policy initiatives) and bottom-up (fishers and NGOs) initiatives that unite efforts from multiple countries with diverse languages, cultures and uneven socio-economic status. This workshop has offered a foundational technical platform on which to further these efforts. This section offers some reminders of region-specific needs, FSA status, some available resources and tools, and recommendations for next steps.

We all depend on these resources and have shared and collective responsibility for their sustainable management.

In response to the identified regional value of FSAs, the increasing threats to the species that form them, and the need for harmonized regional management efforts, the Food and Agriculture Organization (FAO) of the United Nations (UN) created the Spawning Aggregations Working Group (SAWG) under the Western Central Atlantic Fisheries Commission (WECAFC). The group met in 2013, again in 2018 a third meeting in December 2019. The group has made excellent progress in the six years since its inception. The SAWG has agreed on several priorities and developed regional recommendations and workplans for FSA conservation and management (WECAFC 2019). The group has maintained communications through GCFI workshops and annual meetings and through directed listserv (fishspawn-l@listserv.gcfi.org). The SAWG supported development of the regional FSA Fisheries Management Plan and the FSA communications and outreach strategy in the region.

Figure 23. Known FSAs in the Caribbean (green circles) and those that have shown recovery since management measures were enacted (yellow stars).

Importantly, several countries have made great progress in the monitoring assessment and conservation of FSAs (Figure 23). In the Cayman Islands, for example, the Department of Environment, with support of the Grouper Moon Project, has demonstrated assessment and recovery of Nassau grouper using various advanced technologies and increasingly strict legislation and consistent enforcement (see also Heppell et al. this report). The Florida Keys National Marine Sanctuary protected Riley's Hump multi-species FSA site within a large, well-monitored and managed no-take marine zone. FSAs have shown remarkable recovery for several species including mutton snapper, cubera snapper, dog snapper, and black grouper. The US Virgin Islands has also shown recovery of Nassau grouper and red hind and stable populations of yellowfin grouper at several managed spawning aggregation sites in St. Thomas (Nemeth 2005, Kadison et al. 2013, Nemeth et al. 2020).

FSA monitoring and conservation efforts are underway in many other countries and sites throughout the region including the Bahamas, Belize, Mexico, Honduras, Puerto Rico, and Cuba. Current methods used to monitor and assess FSA status are not consistent, hindering site trend analysis, between-site comparisons, and meta-analysis. Adopting a regionally consistent monitoring protocol and associated database would permit more consistent and timely status reports and enhance FSA recovery. (WECAFC 2019; Chollett et al. 2020; Heyman et al. 2019). Several groups around the region (e.g. Belize, Mexico, Honduras, U.S. South Atlantic) have adopted Cooperative Monitoring Protocols – relatively simple and efficient protocols whereby data collection involves participation among managers, scientists, and fishers. The Mexican NGO COBI (Comunidad y Biodiversidad) for example, trained local fishers to monitor FSAs using a standardized protocol (Heyman et al. 2019) and now several FSA sites along the Yucatan coast have

Cooperative FSA monitoring protocols used in the wider Caribbean.

been protected at the behest of the fishermen themselves (Fulton et al. 2018; and see Fulton, this report).

In summary, I offer that while the value of FSAs are equally high among countries and sites throughout the region, there exists an enormous disparity in FSA governance capacity. Nonetheless, regional FSA governance hinges on harmonized policies and legislation, and the adoption and use of common cooperative monitoring protocols and data management systems that foster both site-based and regional status and trends analysis. Success also hinges on the continued inclusion of local fishers in FSA monitoring and conservation. Since not all techniques are appropriate or feasible in every location, existing cooperative monitoring programs offer a suite of standardized and accepted protocols (Table 2; also see Kobara et al. 2013 and more recent protocols in Heyman et al. 2017). These standardized protocols can certainly be updated based on some of the advanced technologies showcased in this workshop. The challenge to the assembled group of experts: Develop and share advanced, yet efficient and appropriate technologies to support cooperative monitoring and enforcement of FSAs.

Experts should continue to develop and share advanced, yet efficient and appropriate technologies to support cooperative monitoring and enforcement of FSAs.

Table 2. FSA monitoring methods (taken from Table 5 in Kobara et al. 2013).

Level	Data collection method	Equipment needs	Data and information generated	Expected output	References, examples and use of these techniques
1	Fisher interviews and port surveys	Access to and trust of fishers, survey instruments or interview forms	Approximate timing, species composition, location, historical exploitation and present status of tFSAs	Traditional knowledge about tFSAs, observations from markets, unverified indications of tFSAs	Johannes 1978, Sadovy et al. 1994, Claro & Lindeman 2003, Hamilton et al. 2005, Ojeda-Serrano et al. 2007, Rhodes & Tupper 2007, Hamilton et al. 2011, Heyman 2011
2	Fishery-dependent surveys	Access to landing sites, measuring boards, scales, otolith processing equipment and microscopes; access to historical catch data	Landings data, gear types, catch per unit effort (CPUE); length-weight frequencies, otolith analysis for age and growth, sex ratios, histological data, biometric information e.g. gonadosomatic indices	Detailed data on extraction from tFSA sites; valuable data for stock assessment; can provide verification of FSA	Beets & Friedlander 1999, Erisman & Allen 2006, Matos-Caraballo et al. 2006, Nemeth et al. 2007b, Rhodes & Tupper 2007, Rhodes et al. 2011
3	Underwater Visual Census (UVC)	SCUBA gear, appropriate breathing mixtures, closed circuit rebreathers (option: sound recorders); video cameras, video laser calipers, remotely operated vehicles (ROV); video drop cameras, GPS (on boat. approximate location)	Area, habitat use, depth, timing, density, length and abundance, behaviour (spawning, courtship, colouration, sound), temperature, qualitative description and benthic mapping of habitat and reef structures; site fidelity	Fish densities, timing of spawning and courtship behaviours; verification that aggregation is for spawning; valuable data for stock assessment; effects of divers on behaviour	Colin 1992, Sadovy et al. 1994, Samoilys 1997, Whaylen et al. 2004, Burton et al. 2005, Heyman et al. 2005, 2010, Pet et al. 2005, Erisman & Allen 2006, Waylen et al. 2006, Nemeth et al. 2007b, Heyman & Kjerfve 2008, Boomhower et al. 2010, Heppell et al 2012
4	Mapping bathymetry, benthic habitat, and fish utilization of tFSAs	Remotely sensed data (Landsat, Ikonos, Quickbird, LiDAR); existing nautical charts and bathymetric maps; GPS; sonar (single beam, dual-beam, multi-beam, or side-scan); Underwater Visual Census data; seabed-mounted or drop video cameras; Autonomous Underwater Vehicles (AUV)	Bathymetric maps, benthic habitat maps showing substratum and biotic cover, rugosity, and slope	General site information can be valuable for MPA delineation; detailed map of spawning aggregation sites showing bathymetry, habitat types, and use by tFSAs	Stumpf et al. 2003, Armstrong et al. 2006, Taylor et al. 2006, Heyman et al. 2007, Kobara & Heyman 2008, Shcherbina et al. 2008, Kobara & Heyman 2010, Coleman et al. 2011
5	Mark and recapture studies using conventional and acoustic tagging and tracking	Standard identification tags, acoustic tags, acoustic receivers (e.g. VR2W)	Site utilization and site fidelity of fishes at FSA sites; time and date of arrival and departure at tFSA site by species, sex, lunar period	Detailed information on temporal aspects of fish utilization of tFSA site including site fidelity, movement patterns, migration pathways	Zeller 1998, Bolden 2000, Nemeth 2005, Starr et al. 2007, Nemeth et al. 2007b, Mann et al. 2009, Rhodes et al. 2012
6	Acoustic monitoring of courtship sounds of fishes	Digital sound recorders (both installed in situ as a monitoring station and mobile, attached to a video camera); rebreathers; baseline of spawning sounds for key species	Quantitative assessments of species' timing and level of participation in spawning based on acoustic monitoring	Monitoring of tFSA site use by various species	Lobel 1992, Mann & Lobel 1995, Holt 2008, Mann et al. 2009, Rowell et al. 2012, Schärer et al. 2012a,b.
7	Oceanographic and meteorological data collection from in situ measurements, and remotely sensed data	Remotely sensed data (Sea surface temperature, sea surface height, ocean colour from MODIS, others), Weather stations, underwater temperature loggers, Acoustic Doppler Current Profilers (ADCP), Electromagnetic current meters, Conductivity Temperature Depth (CTD) meters, Autonomous Underwater Vehicles (AUV), surface drifters, underwater gliders, light meters	Weather patterns, including air temperature, wind speed and direction and rainfall; current speed & direction; hydrostatic pressure, which can offer tide and wave height information; temperature variability and profiles; light intensity; chlorophyll concentrations	Understanding of oceanographic variability, and forcing factors at tFSA sites	Lobel 1978, Colin 1992, Colin 1995, Ezer et al. 2005, Nemeth et al. 2008, Ezer et al. 2010
8	Modelling oceanographic and biophysical connectivity; predicting the location of tFSA sites based on geomorphology; predicting larval transport from known tFSA sites	Three-dimensional numerical simulation models (e.g. Regional Ocean Model (ROMS), Princeton Ocean Model (POM); Oceanographic and bathymetric data; spawning dates, times and locations; larval behaviour; otolith microchemistry; genetics	Predictions of larval connectivity to nursery habitats; local and regional hypothesis-testing about connectivity	Models of larval transport and connectivity; models predicting timing and location of undiscovered tFSAs	Jones et al. 1999, Paris & Cowen 2004, Ezer et al. 2005, Jones et al. 2005, Paris et al. 2005, Kobara & Heyman 2006, Elsdon et al. 2008, Ezer et al. 2010, Boomhower et al. 2010, Kobara & Heyman 2010, Chérubin et al. 2011, Karnauskas et al. 2011

IX. Closing remarks and charge to workshop participants

The workshop was concluded by going around the room and having each participant articulate one outcome from the workshop that they would take back and would apply to their own work, or alternatively, one “action item” that they wanted to recommend to the larger group. Generally, participants were able to identify specific insights gained during the two-day workshop that would influence the way they approached fishery management in their own regions. These approaches ranged from foundational exploratory steps, such as putting a hydrophone on a fishing boat to go document new FSAs, to tweaking long-standing monitoring programs in new ways. For example, there was recognition that the relationships between FSA counts and population abundance may not be direct, and that certain assumptions need to be further tested.

Other specific recommendations or action items were as follows:

- Developing advanced technologies to support FSA enforcement in close or managed areas.
- Communicating the importance of FSA management to fishery management bodies, particularly within the context of ecosystem-based management.
- Improved user-interfaces on analysis packages to ameliorate the burden on regions that lack in-house capacity for post-processing.
- Continue developing ways to share knowledge and technology, increase capacity on-site, and support research and development to make technology lower in cost and more accessible.
- Recognize that best-laid plans are bound to fail without adequate community support, and integrate managers and social scientists into future workshops.
- Continue integrating fishermen into the workshops so that they can become aware of technologies and bring these back to their communities, increasing the capacity for citizen science.
- Continue to encourage academic partners to collaborate and understand the science needed to help governments and regulatory bodies make more effective management decisions.
- Continue to network and share resources, training opportunities, and new technologies.

X. 2020 and beyond - Workshop evaluation and initial input for the next GCFI-NOAA workshops

A common outcome from each of the GCFI-NOAA workshops has been an increased sense of collaboration and strengthening of a network of experts and practitioners in ecosystem management and conservation. Evaluation of the workshop was positive; participants felt that the agenda clearly established expectations for participants and objectives and outcomes for the workshop. Participants noted they enjoyed the mix of plenary talks, focused discussion, and open forum. The presentations highlighted emerging technologies and demystified some advanced technologies that many participants thought were either too expensive or too complicated. There was a broad appreciation for the importance of developing collaborations in order to share resources, especially among agencies or nations that have more assets or access to technologies with developing nations. Many evaluations reported the FSA case studies as being the most valuable. A broad spectrum of expertise, from engineers and statisticians to field technicians and community organizers, offered a variety of approaches that could be brought to bear on management of FSAs considering a wide range of funding and resources available.

Suggestions to improve the next FSA workshop included inviting more fishers to participate so they can learn about available technologies, especially those that can be easily deployed on fishing vessels, or citizen-science methods that could be used by fishing and dive organizations to augment monitoring programs. Participants also wanted to hear more directly from resource managers who have made decisions to protect FSAs: what data did they rely upon for their decision-making? A few individuals also wanted to learn about even more examples of FSAs and the challenges they face in developing monitoring programs. Lastly, several participants wanted more discussion of measures and technologies that could be used to improve the compliance and law enforcement of existing closed areas for protecting FSAs.

Lastly, workshop participants provided input into the next topics that could be addressed through GCFI workshops. The following were identified as priorities.

1) Design and operation of inexpensive acoustic and camera systems.
2) Machine learning and automation in analysis or interpretation of acoustic and video data for fish and habitat assessments.
3) Cost effective autonomous or remotely operated vehicles.

XI. References

Aburto-Oropeza, O., C. López-Sagástegui, M. Moreno-Baáez, I. Mascareñas-Osorio, V. Jiménez-Esquivel, A.F. Johnson, and B. Erisman. 2017. Endangered species, ecosystem integrity, and human livelihoods. Conservation Letters 11:1-8.

Aggarwal. C.C. 2018. Neural networks and deep learning. Springer. 497 p.

Apel, A., and B.E. Erisman. 2012. Productivity and susceptibility analysis of the Gulf corvina (*Cynoscion othonopterus*). Technical Report to the Environmental Defense Fund. 10 p.

Archer, S.K., S.A. Heppell, B.X. Semmens, C.V. Pattengill-Semmens, P.G. Bush, C.M. McCoy, and B.C. Johnson. 2012. Patterns of color phase indicate spawn timing at a Nassau grouper Epinephelus striatus spawning aggregation. Current Zoology. 58 (1): 73-83.

Archer, S.K., J.E. Allgeier, B.X. Semmens, S.A. Heppell, C.V. Pattengill-Semmens, A.D. Rosemond, P.G. Bush, C.M. McCoy, B.C. Johnson, and C.A. Layman. 2014. Hot moments in spawning aggregations: implications for ecosystem-scale nutrient cycling. Coral Reefs. 10.1007/s00338-014-1208-4.

Asch, R.G., and B. Erisman. 2018. Spawning aggregations act as a bottleneck influencing climate change impacts on a critically endangered reef fish. Diversity and Distributions 24(12): 1712-1728.

Bengio, Y., A. Courville, and P. Vincent. 2013. Representation learning: A review and new perspectives. IEEE Transactions on Pattern Analysis and Machine Intelligence. 35(8): 1798-1828.

Bertucci, F., P. Lejeune, J. Payrot, and E. Parmentier. 2015. Sound production by dusky grouper *Epinephelus marginatus* at spawning aggregation sites. Journal of Fish Biology 1,1-22. https://doi.org/10.1111/jfb.12733

Bishop, C. 2006. Pattern recognition and machine learning. Springer Science and Business Media LLC. 733 p.

Breiman, L. 2001. Random forests. Machine Learning. 45(1): 5-32. https://doi.org/10.1023/A:1010933404324

Charnaak, E. 2018. Introduction to deep learning. The Massachusetts Institute of Technology. 174 p.

Chérubin, L.M., F. Dalgleish, A. Ibrahim, M. Schärer, R.S. Nemeth, and R. Appeldoorn. 2020. Fish spawning aggregations dynamics as inferred from a novel, persistent presence robotic approach. Frontiers in Marine Science, 6:1-19.

Chollett, I., Priest, M., Fulton, S., and Heyman, W. D. 2020. Should we protect extirpated fish spawning aggregation sites? Biological Conservation, 241, 108395.

Cisneros-Mata, M.A., G. Montemayor-López, and M.J. Román-Rodríguez. 1995. Life history and conservation of *Totoaba macdonaldi*. Conservation Biology 9:806-814.

Cummings, N.J., M. Karnauskas, A. Rios, W.J. Harford, R. Trumble, R. Glazer, A. Acosta, and W.L. Michaels. 2017. Report of a GCFI workshop: Best practices and trade-offs for selecting between fishery-dependent and fishery-independent sampling in data-limited regions. Gulf and Caribbean Fisheries Institute Conference, Panama City, Panama. November 9-13, 2015. NMFS-SEFSC-711. 26 p. https://doi.org/10.7289/V5/TM-SEFSC-711.

Dawkins, M., L. Sherrill, K. Fieldhouse, A. Hoogs, B. Richards, D. Zhang, L. Prasid, et. al. 2017. An open source platform for underwater image and video analytics. *In* 2017 IEEE Winter Conference on Applications of Computer Vision (WACV), p. 898-906. IEEE.

Egerton, J.P., A.F. Johnson, L. Le Vay, C.M. McCoy, B.X. Semmens, S.A. Heppell, and J.R. Turner. 2017. Hydroacoustics for the discovery and quantification of Nassau grouper (*Epinephelus striatus*) spawning aggregations. Coral Reefs. 36 (2): 589-600.

Erisman, B.E., O. Aburto-Oropeza, A. Apel, and R. Fujita. 2012a. An assessment of risks to the Gulf corvina fishery. Technical Report to the Grupo Technico Corvina (GTC). 19 p.

Erisman, B., O. Aburto-Oropeza, C. Gonzalez-Abraham, I. Mascareñas-Osorio, M. Moreno-Báez, and P.A. Hastings. 2012b. Spatio-temporal dynamics of a fish spawning aggregation and its fishery in the Gulf of California. Scientific Reports 2:284.

Erisman, B., W. Heyman, S. Kobara, T. Ezer, S. Pitman, O. Aburto-Oropeza, and R.S. Nemeth. 2017. Fish spawning aggregations: where well-place management actions can yield big benefits for fisheries and conservation. Fish and Fisheries 18:128-144.

Erisman, B., A. Grüss, I. Mascareñas-Osorio, H. Lícon-González, A.F. Johnson, and C. López-Sagástegui. 2019. Balancing conservation and utilization in spawning aggregation fisheries: a trade-off analysis of an overexploited marine fish. ICES Journal of Marine Science fsz195, https://doi.org/10.1093/icesjms/fsz195.

Erisman, B., A. Grüss, A. Johnson, H. Licon, I. Mascareñas-Osorio, A. Johnson, C. López-Sagástegui. 2020. Balancing conservation and utilization in spawning aggregation fisheries: a trade-off analysis of an overexploited marine fish. ICES Journal of Marine Science 77: 148-161.

Erisman, B.E., and T.J. Rowell. 2017. A sound worth saving: acoustic characteristics of a massive fish spawning aggregation. Biology Letters 13: 20170656.

Erisman, B.E., A. Apel, and R. Fujita. 2013. The influence of variations in life history parameters on a virtual population analysis of the Gulf Corvina (*Cynoscion othonopterus*). Technical Report to the Environmental Defense Fund. 15 p.

Erisman, B.E., A. Apel, A. MacCall, M.J. Román, and R. Fujita. 2014. The influence of gear selectivity and spawning behavior on a data-poor assessment of a spawning aggregation fishery. Fisheries Research 159:75-87.

Fish, M.P. and W.H. Mowbray, 1970. Sounds of Western North Atlantic fishes. A reference file of biological underwater sounds. The John Hopkins Press, Baltimore, MD. 207 p.

Fulton, S., J. Caamal-Madrigal, A. Aguilar-Perera, L. Bourillón, and W.D. Heyman. 2018. Marine conservation outcomes are more likely when fishers participate as citizen scientists: Case studies from the Mexican Mesoamerican Reef. Citizen Science: Theory and Practice 3(1): 1-12. https://doi.org/10.5334/cstp.118

Gedamke, T., and B.E. Erisman. 2012. Evaluation of available data, preliminary data-poor assessment and recommendations for the Gulf corvina fishery in the Gulf of California. Technical Report to the Environmental Defense Fund. 39 p.

Gerhardinger, L.C., R.C. Marenzi, A.A. Bertoncini, R.P. Medeiros, and M. Hostim-Silva. 2006. Local ecological knowledge on the Goliath grouper *Epinephelus itajara* (Teleostei: Serranidae) in Southern Brazil. Neotropical Ichthyology 4(4):441-450.

Geron, A. 2017. Hands-on machine learning with Scikit-Learn and TensorFlow. Concepts, tools, and techniques to build intelligent systems. O'Reilly Media Inc. 556 p.

Gherard, K.E., B.E. Erisman, O. Aburto-Oropeza, K. Rowell, and L.G. Allen. 2013. Fishery-dependent estimates of growth, development, and reproduction in Gulf corvina (*Cynoscion othonopterus*). Bulletin of the Southern California Academy of Sciences 112:1-18.

Giglio, V.J., J.R. Leite, M.O. Freitas, and M. Hostim-Silva. 2016. Mapping goliath grouper aggregations in the southwestern Atlantic. Brazilian Journal of Oceanography 64(4): 83-86.

Gordon, T.A.C., A.N.Radford, and I.K. Davidson et al. 2019. Acoustic enrichment can enhance fish community development on degraded coral reef habitat. Nat. Commun. 1–7. https://doi.org/10.1038/s41467-019-13186-2

Heppell, S.A., B.X. Semmens, S.K. Archer, C.V. Pattengill-Semmens, P.G. Bush, C.M. McCoy, S.S. Heppell, and B.C. Johnson. 2012. Documenting recovery of a spawning aggregation through size frequency analysis from underwater laser calipers measurements. Biological Conservation. 155: 119-127.

Heppell, S.A., B.X. Semmens, C.V. Pattengill-Semmens, P.G. Bush, B.C. Johnson, C.M. McCoy, C. Paris, J. Gibb, and S.S. Heppell. 2008. Tracking potential larval dispersal patterns from Nassau grouper aggregation sites: Evidence for local retention and the “importance of place”. *In* Proceedings of the 61st Annual Gulf and Caribbean Fisheries Institute; p. 325-327, Guadeloupe, November, 2008.

Heppell, S.A., B.X.Semmens, C.V.Pattengill-Semmens, P.G. Bush, C.M. McCoy, and B.C. Johnson. 2013. Behavior, hyperstability, and population declines of an aggregating marine fish. *In* Proceedings of the 66th Gulf and Caribbean Fisheries Institute, Corpus Christi, Texas USA: Gulf and Caribbean Fisheries Institute.

Heyman, W.D., Fulton, S., Erisman, B. y Aburto-Oropeza, O. 2017. Protocolos de monitoreo e investigación participativa para agregaciones reproductivas de peces en México. Comunidad y Biodiversidad A.C., Guaymas, Sonora, Mexico & LGL Ecological Research Associates, Inc. Bryan, TX, Estados Unidos. 40 p.

Heyman, W.D., A. Grüss, C.R. Biggs, S. Kobara, N.A. Farmer, M. Karnauskas, S. Lowerre-Barbieri, and B. Erisman. 2019. Cooperative monitoring, assessment, and management of fish spawning aggregations and associated fisheries in the U.S. Gulf of Mexico. Marine Policy 109:103689.

Hu, Y., J.E. Majoris, P.M. Buston, and J.F. Webb. 2019. Potential roles of smell and taste in the orientation behavior of coral-reef fish larvae: insights from morphology. Journal of fish Biology 95: 311-323

Ibrahim, A.K., H. Zhuang, L.M. Chérubin, M.T. Schärer Umpierre, F. Dalgleish, N. Erdol, B. Ouynag, A, Dalgleish. 2018a. An approach for automatic classification of grouper vocalizations with passive acoustic monitoring. J. Acous. Soc. Am., 143:2, 666-676.

Ibrahim, A.K., L.M. Chérubin, H. Zhuang, M.T. Schärer Umpierre, and N. Erdol. 2018b. Automatic classification of grouper species by their sounds using deep neural networks. The Journal of the Acoustical Society of America 144, EL196 (2018); https://doi.org/10.1121/1.5054911.

Ibrahim, A.K., H. Zhuang, L.M. Chérubin, M.T. Schärer Umpierre, A.M. Ali, R. S. Nemeth, and N. Erdol. 2019. Classification of red hind grouper call types using random ensemble of stacked autoencoders. The Journal of the Acoustical Society of America 146:4, 2155-2162.

Jackson, A.M., B.X. Semmens, Y. Sadovy de Mitcheson, R.S. Nemeth, S.A. Heppell, P.G. Bush, A. Aguilar-Perera, J.A.B. Claydon, M.C. Calosso, K.S. Sealey, M.T. Schärer, and G. Bernardi. 2014. Population structure and phylogeography in Nassau grouper (*Epinephelus* *striatus*), a mass-aggregating marine fish. PLoS ONE. https://doi.org/10.1371/journal.pone.0097508.

Kadison, E., Nemeth, R.S., Blondeau, J., Smith, T., Calnan, J. 2013. Nassau grouper (*Epinephelus striatus*) in St. Thomas, US Virgin Islands, with evidence for a spawning aggregation site recovery. *In* Proceedings of the 66th Gulf and Caribbean Fisheries Institute. Presented at the Gulf and Caribbean Fisheries Institute, Gulf and Caribbean Fisheries Institute, p. 273–279.

Kelleher, J.D., B. MacNamee, and A. D'Arcy. 2015. Fundamentals of Machine Learning for predictive data analytics: algorithms, worked examples, and case studies. Massachusetts Institute of Technology. 595 p.

Koenig, C.C., F.C. Coleman, and K.C. Kingon. 2011. Pattern of recovery of the goliath grouper *Epinephelus itajara* (Lichtenstein, 1822) population in the southeastern U.S. Bulletin of Marine Science 87(4): 891-911.

Kobara S., Heyman W.D., Pittman S.J. and Nemeth R.S. 2013. Biogeography of transient reef-fish spawning aggregations in the Caribbean a synthesis for future research and management. Oceanography and Marine Biology: An Annual Review 51:281-236.

Kong, Y., T. Yu. 2018. A deep neural network model using random forest to extract feature representation for gene expression data classification. Nature Scientific Reports 8(4):16477.

Leis, J. M. 2015. Is dispersal of larval reef fishes passive? *In* Ecology of Fishes on Coral Reefs (C. Mora, ed.), p. 223–226. Cambridge University Press, Cambridge.

Locascio, J. V., and Burton, M.L. 2015. A passive acoustic survey of fish sound production at Riley's hump within Tortugas south ecological reserve; implications regarding spawning and habitat use. Fishery Bulletin 114:103–116. https://doi.org/10.7755/FB.114.1.9

Luckhurst, B.E. 2010. Observations of a Black Grouper (Mycteroperca bonaci) spawning aggregation in Bermuda. Gulf and Caribbean Research 22: 43-49.

Luczkovich, J.J., Mann D.A., Rountree R.A. 2008. Passive Acoustics as a Tool in Fisheries Science. Trans Am Fish Soc 137:533–541. https://doi.org/10.1577/t06-258.1

MacCall, A., B.E. Erisman, A. Apel, and R. Fujita. 2011. Data-poor models for assessing the fishery for the Gulf curvina and evaluating management alternatives. Technical Report to the Grupo Technico Corvina. 11 p.

Mann, D.A., J.V. Locascio, F.C. Coleman, and C.C. Koenig. 2009. Goliath grouper *Epinephelus itajara* sound production and movement patterns on aggregation sites. Endangered Species Research 1:1-8. https://doi.org/10.3354/esr00109

Mann, D.A., J.V. Locascio, M.T. Schärer, M.I. Nemeth, and Appeldoorn, R.S. 2010. Sound production by red hind *Epinephelus guttatus* in spatially segregated spawning aggregations. Aquatic Biology 10:149–154. https://doi.org/10.3354/ab00272

Michaels, W.L., B. Binder, K. Boswell, L.M. Chérubin, D.A. Demer, T. Jarvis, F.R. Knudsen, C. Lang, J.E. Paramo, P.J. Sullivan, S. Lillo, J.C. Taylor, and C.H. Thompson. 2019a. Best Practices for Implementing Acoustic Technologies to Improve Reef Fish Ecosystem Surveys: Report from the 2017 GCFI Acoustics Workshop. NOAA Tech. Memo. NMFS-F/SPO-192, 161 p.

Michaels, W.L., N.O. Handegard, K. Malde, and H. Hammersland-White (eds). 2019b. Machine learning to improve marine science for the sustainability of living ocean resources: Report from the 2019 Norway - U.S. Workshop. NOAA Tech. Memo. NMFS-F/SPO-199, 107 p.

MAGLA (Ministry of the Attorney General and Legal Affairs). 2015. Laws of Trinidad and Tobago. Fisheries Act, Chapter 67:51, Act 39 of 1916. 1-25.

Nemeth, R.S. 2005. Population characteristics of a recovering US Virgin Islands red hind spawning aggregation following protection. Marine Ecology Progress Series 286:81-97.

Nemeth, R.S., E. Kadison, N.J. Brown Peterson, J. Blondeau 2020. Reproductive biology and behavior associated with a spawning aggregation of the yellowfin grouper *Mycteroperca venenosa*. Bull. Mar. Sci. 96:96(1):31–56. https://doi.org/10.5343/bms.2019.0028

NOAA. 2016. Endangered and Threatened Species: Final Listing Determinations for Nassau grouper. Fed. Register 81:42268-85.

Olsen, D.A., and J.A. LaPlace. 1978. A study of Virgin Islands grouper fishery based on a breeding aggregation, Gulf and Caribbean Fisheries Institute, 31:130-144.

Ortiz, R., I. Mascareñas-Osorio, M. Román, and J. Castro. 2016. Biological and fisheries monitoring of the Gulf Corvina in the Upper Gulf of California. DataMares. InteractiveResource. https://doi.org/10.13022/M38590.

Paredes, G.A., B.E Erisman, I. Mascarenas Osorio, J.J. Cota Nieto, K. Gherard, and O. Aburto-Oropeza. 2010. La Curvina Golfina: Biology, Pesqueria y Su Gente. Biodiversitas 91:1-5.

Pitt, J., T. Warren, and C. Trott. 2018. Managing Fish Spawning Aggregations in a Changing Climate: A Case Study of Red Hind (*Epinephelus guttatus*) in Bermuda. Gulf and Carib. Fisheries Institute Proceedings, p. 301-308.

Reid, E. 2017. Relationships between climate, growth, and fisheries production in a commercially exploited marine fish. M.S. thesis, University of Texas at Austin. 55 p.

Richards, B.L., O. Beijbom, M.D. Campbell, E.M. Clarke, G. Cutter, M. Dawkins, D. Edgington, D.R. Hart, M.C. Hill, A. Hoogs, D. Kriegman, E.E. Moreland, T.A. Oliver, W.L. Michaels, M. Piacentino, A.K. Rollo, C. Thompson, F. Wallace, I.D. Williams, and K. Williams. 2019. Automated Analysis of Underwater Imagery: Accomplishments, Products, and Vision. NOAA Technical Memorandum NOAA-TM-NMFS-PIFSC-83. 58 p. https://doi.org/10.25923/0cwf-4714.

Román-Rodríguez, M.J. 2000. Estudio pobacional del chano norteno, Micropogonias megalops y la curvina Golfina *Cynoscion othonopterus* (Gilbert) (Pisces: Sciaenidae), especies endemicas del alto Golfo California, Mexico. Instituto del Medio Ambiente y Desarrollo Sustentable del Estado de Sonora. Informe final SNIB-CONABIO proyecto No. L298. Mexico D.F. 143 p.

Rowell, T.J., Appeldoorn R.S., Rivera J.A., et. al. 2010. Use of passive acoustics to map grouper spawning aggregations, with emphasis on red hind, *Epinephelus guttatus*, off Western Puerto Rico. 63rd Gulf and Caribbean Fisheries Institute Proceedings, p. 139–142.

Rowell, T.J., M.T. Schärer, R.S. Appeldoorn, M.I. Nemeth, D.A. Mann, and Rivera, J.A. 2012. Sound production as an indicator of red hind density at a spawning aggregation. Marine Ecology Progress Series 462, 241-250 https://doi.org/10.3354/meps09839

Rowell, T.J., R.S. Nemeth, M.T. Schärer, and Appeldoorn, R.S. 2015. Fish sound production and acoustic telemetry reveal behaviors and spatial patterns associated with spawning aggregations of two Caribbean groupers. Marine Ecology Progress Series 518, 239–254

Rowell, T.J., D.A. Demer, O. Aburto-Oropeza, J.J. Cota-Nieto, J.R. Hyde, and Erisman, B.E. 2017. Estimating fish abundance at spawning aggregations from courtship sound levels. Scientific Reports 7, 1–14. https://doi.org/10.1038/s41598-017-03383-8

Rowell, T.J., M.T. Schärer, and Appeldoorn, R.S. 2018. Description of a new sound produced by Nassau grouper at spawning aggregation sites. Gulf and Caribbean Research 29, 22-26 https://doi.org/10.18785/gcr.2901.12

Ruelas-Peña, J., C. Valdez-Muñoz, and E. Aragón-Noriega. 2017. Analysis of the corvina gulf fishery as a function of management actions in the Upper Gulf of California, Mexico. Latin American Journal of Aquatic Research. 41:498-505.

Russel, S.J., P. Norvig. 2010. Artificial intelligence: A modern approach. Third Edition. Prentice Hall.

Sadovy, Y. 1994. Grouper stocks of the western Atlantic: the need for management and management needs. Gulf and Caribbean Fisheries Institute, 43:43-64.

Sadovy, Y. and M. Domeier. 2005. Are aggregation-fisheries sustainable? Reef fish fisheries as a case study. Coral Reefs 24:254-262.

Sadovy De Mitcheson, Y., Cornish, A., Domeier, M., Colin, P.L. Russell, M., Lindeman, K.C., 2008. A global baseline for spawning aggregations of reef fishes. Conservation Biology 22:1233–1244.

Sadovy de Mitcheson, Y., and B. Erisman. 2012. Fishery and biological implications of fishing spawning aggregations, and the social and economic importance of aggregating fishes. In Reef fish spawning aggregations: biology, research and management (Y. Sadovy de Mitcheson and P. Colin, eds.), p. 225-284. Springer, New York.

Schärer, M.T., M.I. Nemeth, D.A. Mann, J.V. Locascio, R.S. Appeldoorn. and T.J. Rowell 2012a. Sound production and reproductive behavior of yellowfin grouper, *Mycteroperca venenosa* (Serranidae) at a spawning aggregation. Copeia 2012: 135-144

Schärer, M.T., T.J. Rowell, M.I. Nemeth, and Appeldoorn, R.S. 2012b. Sound production associated with reproductive behavior of Nassau grouper *Epinephelus striatus* at spawning aggregations. Endangered Species Research 19,29–38. https://doi.org/10.3354/esr00457

Semmens, B.X., K.E. Luke, P.G. Bush, C.V. Pattengill-Semmens, B. Johnson, C. McCoy, S. Heppell. 2005. Investigating the reproductive migration and spatial ecology of Nassau grouper (*Epinephelus striatus*) on Little Cayman Island using acoustic tags – An Overview. 58th Gulf and Caribbean Fisheries Institute Meeting Proceedings.

Sherman, K.D., J.R. Paris, R.A. King, K.A. Moore, C.P. Dahlgren, L.C. Knowles, K. Stump, C.R. Tyler, and J.R. Stevens. 2020. RAD-seq analysis and in situ monitoring of Nassau grouper reveal fine-scale population structure and origins of aggregating fish. Frontiers in Marine Science 7:157. https://doi.org/10.3389/fmars.2020.00157

Stock, B.C., S.A. Heppell, L. Waterhouse, I.C. Dove, C.V. Pattengill-Semmens, C.M. McCoy, P.G. Bush, G. Ebanks-Petrie, and B.X. Semmens. In review. Pulse recruitment and recovery of Cayman Islands Nassau grouper (*Epinephelus striatus*) spawning aggregations revealed by in situ length-frequency data. ICES Journal of Marine Science.

Stone, V.J. 2019. Artificial intelligence engines. Sebtel Press. 201 p.

Taulli, T. 2019. Artificial basics: A non-technical introduction. Springer Science and Business Media LLC. 185 p.

Taylor, J.C., D.B. Eggleston, and P.S. Rand. 2006. Nassau grouper (*Epinephelus striatus*) spawning aggregations: hydroacoustic surveys and geostatistical analysis. *In* Emerging Technologies for Reef Fisheries Research and Management (J.C. Taylor, ed.), p. 18-25. NOAA Professional Paper NMFS 5.

Tuohy, E., M. Schärer-Umpierre, and R. Appeldoorn. 2017. Spatio-Temporal Dynamics of a Nassau grouper spawning aggregation in Puerto Rico. *In* Proceedings of the 69th Gulf and Caribbean Fisheries Institute, p. 319–321.

Wall, C.C., C. C. Wall P. Simard, M. Lindemuth, C. Lembke, D. F. Naar, C. Hu, B. B. Barnes, F. E. Muller-Karger, and D. A. Mann. 2014. Temporal and spatial mapping of red grouper *Epinephelus morio* sound production. J Fish Biol 85:1470–88. https://doi.org/10.1111/jfb.12500

Waterhouse, L., S.A. Heppell, C.V. Pattengill-Semmens, C. McCoy, P. Bush, B.C. Johnson, and B.X. Semmens. 2020. Recovery of critically endangered Nassau grouper (*Epinephelus striatus*) in the Cayman Islands following targeted conservation actions. Proceedings of the National Academy of Sciences 117(3):1587-1595. https://doi.org/10.1073/pnas.1917132117.

WECAFC (Western Central Atlantic Fishery Commission). 2019. Report of the second meeting of the CFMC/WECAFC/OSPESCA/CRFM Spawning Aggregations Working Group (SAWG), Miami, Florida, 27–29 March 2018. FAO Fisheries and Aquaculture Report. No. 1261. Western Central Atlantic Fishery Commission. Bridgetown.

Whaylen, L., C.V. Pattengill-Semmens, B.X. Semmens, P.G. Bush, and M.R. Boardman. 2004. Observations of a Nassau grouper spawning aggregation site in Little Cayman, including multi-species spawning. Environmental Biology of Fishes. 70:305-313.

Whaylen, L., P.G. Bush, B.C. Johnson, K.E. Luke, C.M.R. McCoy, S. Heppell, B.X. Semmens, and M. Boardman. 2006. Aggregation dynamics and lessons learned from five years of monitoring at a Nassau grouper spawning aggregation in Little Cayman. 59th Gulf and Caribbean Fisheries Institute Meeting Proceedings.

Wielgus, J. and B.E. Erisman. 2012. Demographic analyses of the Gulf corvina (*Cynoscion othonopterus*). Technical Report to the Environmental Defense Fund. 9p.

Wilson, K.C., B.X. Semmens, C.V. Pattengill-Semmens, C. McCoy, and A. Širović. 2020. Potential for grouper acoustic competition and partitioning at a multispecies spawning site in Little Cayman, Cayman Islands. Marine Ecology Progress Series, 634: 127-146. https://doi.org/10.3354/meps13181.

Zayas-Santiago, C., Appeldoorn R., Schärer-Umpierre, M., and J. Cruz-Motta. 2019. Red hind *Epinephelus guttatus* vocal repertoire characterization, behavior and temporal patterns. Gulf and Caribbean Fisheries Institute, November 2019.

XII. Appendices

Appendix A. Terms of Reference and Agenda

TERMS OF REFERENCE

Background:

The 2-day GCFI workshop will be held on November 2-3, 2019, preceding the 72nd GCFI conference in Punta Cana, Dominican Republic from November 4-8, 2019. The workshop is the third in a series that aims to build capacity and advance the use of integrated technologies to enhance fisheries assessments in coral reef ecosystems. The focus for 2019 is how best to apply integrated and emerging technologies to improve research, monitoring, and abundance estimation for reef fish spawning aggregations (FSAs).

Workshop Goals:

This workshop will review progress made since the last 2009 GCFI workshop on FSAs in the Caribbean (Kobara et al. 2013) and address a work plan and priority recommendations identified in the Western Central Atlantic Fishery Commission 2018 Report, specifically to "Develop and activate a regional cooperative monitoring system for FSAs" and "Share technical capacity for FSA identification, characterization, monitoring and conservation." The two primary goals of the workshop are: 1) to enhance scientific capacity within the GCFI community and establish best-practices in conducting research and monitoring of FSA's using integrated technologies, and 2) to evaluate the scientific data requirements for stock management (e.g., ensuring sustainable populations) and spatial management (e.g., conserving single or multi-species spawning aggregations) strategies.

Key Questions and Information Gaps:

1. Are data from FSAs for stock assessments a valuable end goal? What are the expected data streams that would be most useful to integrate into a stock assessment process?
2. How representative is one or a few FSAs to the population? What percentage of the fish in an area use a particular FSA?
3. How do FSAs change over time, and can it be related to management actions? How do the dynamics of the aggregation change in terms of use, do aggregations reoccupy other sites?
4. What does a recovering FSA look like? What is the meaning of trends in abundance? What monitoring design is required? What is the fate of an extirpated FSA? What do zeros actually mean?
5. What are the challenges with assessing and managing single versus multi-species aggregations? How can technologies assist with the design and enforcement of FSA protection measures?

To answer these questions, we will approach each problem using the following guideposts:

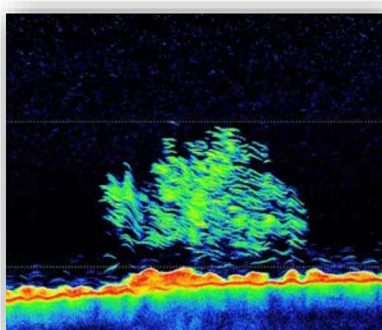
What is known about this topic? How important is this gap for improving management of the species? What technologies are available to address this gap?

Workshop Objectives:

A. Summarize the state-of-science of FSA monitoring, assessment, management and protection of resident and transient spawning aggregations in the region.
B. Evaluate and provide guidance on the use of integrated technologies to enhance research and survey operations and reduce sources of uncertainty on FSAs to address various informational requirements for managers such as biomass estimation, spatio-temporal variability, and essential habitat.
C. Identify the feasibility and limitations (i.e. technical, financial) in deploying technologies, and provide recommendations in the design of cost-effective FSA survey programs in support of fishery and spatial management decisions.

Expected outcomes:

1. A *workshop report* that addresses calls for enhancing FSA monitoring programs with the integration of technologies in support of fishery and ecosystem management.
2. Recommendations for proposal(s) to conduct field experiments that evaluate new technologies and develop best practices in using integrated technologies for FSA assessments and research.



AGENDA

Day 1: Saturday, November 2nd

9:30 Arrival and welcome

10:00 Introductions of participants

10:10 Scope and workshop Terms of Reference

10:20 Review of participant survey responses and workshop expectations

Morning Plenary Session 1: FSAs: From Data Collection to Resource Management

10:30 Keynote Presentations and Forum

Keynote 1: Public-private-academic partnership leads to FSA conservation success in the Cayman Islands - Scott Heppell (Oregon State University) and Brice Semmens (Scripps Institute and UC San Diego)

Keynote 2: The evolution of monitoring a commercially-targeted fish spawning aggregation: lessons learned from Gulf corvina - Brad Erisman (University of Texas) and Tim Rowell (NOAA Northeast Fisheries Science Center)

11:30 Ice-breaker FSA assessment exercise

12:00 Lunch break

1:30 Review results of group exercise

Breakout Session 1: How Do We Document Trends and Interpret Them for Management?

2:00 Address key questions and information gaps in FSA research and monitoring;
What is known? Why is it important to management? What technologies are available?

3:30 Coffee break

4:00 Report-out from breakout groups

4:45 Recap of day 1 and prepare for day 2

5:00 Adjourn and proposal for social hour and dinner

Day 2: Sunday, November 3rd

9:00 Welcome and review of day 1

Morning Plenary Session 2: Technologies for FSA Research and Monitoring Panel

9:15 Review of activities from previous GCFI workshops

Enhance capacity and advance the use of integrated technologies for fish and coral reef ecosystem assessments – Bill Michaels (NMFS Science and Technology)

9:45 Plenary presentations: emerging technologies for FSA research and monitoring

Overview of autonomous platforms and technologies – Dave Demer (NOAA Southwest Fisheries Science Center) and Laurent Chérubin (Florida Atlantic University)

Identifying FSAs with cost effective passive acoustic technologies – Michelle Schärer (HJR Reefscaping)

How will machine learning and artificial intelligence change how we conduct FSA research and monitoring? – Bill Michaels and Charles Thompson (NOAA Southeast Fisheries Science Center)

10:45 Coffee break

Breakout Session 2: Recommendations for FSA Research and Monitoring Programs

11:00 Breakout Groups led by representatives from FSA study sites – *Stuart Fulton (COBI, Mexico); Joanna Pitt (Bermuda); Dani Morley (Florida FWC); Brad Erisman (Univ. of Texas); Kelly Kingon (Univ. of Trinidad and Tobago)*

Participants will provide expertise and recommendations for existing or new technologies under low, medium and high funding resource scenarios

12:00 Lunch break

1:00 Breakout session 2 (continued)

2:30 Report-out on research and monitoring program recommendations

3:00 Coffee break

3:30 Review progress and potential for building on FSA research across the Gulf and Caribbean

4:00 Closing Remarks, workshop wrap-up and evaluation

4:30 Adjourn and continue discussions on potential proposals

Appendix B. Participant and Steering Committee

Workshop Participants

Last name	First Name	Affiliation	Email
Acosta	Alejandro	Florida Fish and Wildlife Conservation Commission	Alejandro.acosta@myfwc.com
Appeldoorn	Eric	University of Puerto Rico	eric.appeldoorn1@upr.edu
Bolser	Derek	University of Texas	derekbolser@utexas.edu
Caamal	Jacobo	COBI Mexico	jcaamal@cobi.org.mx
Caillouet	Ryan	NOAA Fisheries Southeast Fisheries Science Center	ryan.caillouet@noaa.gov
Campbell	Matt	NOAA Fisheries Southeast Fisheries Science Center	Matthew.d.campbell@noaa.gov
Candelmo	Allison	REEF	alli@reef.org
Chérubin	Laurent	Florida Atlantic University	lcherubin@fau.edu
DeMaria	Don	Fisher, Florida Keys	dondemaria@aol.com
Demer	David	NOAA Fisheries Southwest Fisheries Science Center	David.demer@noaa.gov
Erisman	Bradley	University of Texas Marine Science Institute	berisman@utexas.edu
Fulton	Stuart	COBI	sfulton@cobi.org.mx
Galvis	Nohora	Observatorio Pro Arrecifes, Fundación ICRI	icri.colombia@gmail.com
Giró-Peterson	Ana	Healthy Reef Initiative	anagiro@gmail.com
Gittings	Steve	NOAA Office of National Marine Sanctuaries	steve.gittings@noaa.gov
Guzman	Osvaldo	COBI Mexico	balamguz92@gmail.com
Heppell	Scott	Oregon State University	scott.heppell@oregonstate.edu
Heyman	Will	LGL Associates	wheyman@lgl.com
Hill	Ron	NOAA Fisheries	ron.hill@noaa.gov
Johnson	Bradley	Cayman DOE	Bradley.Johnson@gov.ky
Karnauskas	Mandy	NOAA Fisheries	mandy.karnauskas@noaa.gov
Kingon	Kelly	University of Trinidad and Tobago	kelly.kingon@utt.edu.tt
Kuramae Izioka	Ayumi	Saba Bank National Park	ayumikuramae@gmail.com
Legge	Aaron	Vemco - Innovasea, Canada	a.legge@innovasea.com
Lowerre-Barbieri	Sue	Univ. Florida/FWRI	susan.barbieri@myfwc.com
Maldonado	Andres	Fisher, Puerto Rico	andres.scuba@gmail.com
Mayorga	Melissa	Univ. Veracruzana, Instituto de Ciencias Marinas y Pesquerías	mmayorga@gmail.com
Michaels	William	NOAA Fisheries Office of Science and Technology	william.michaels@noaa.gov
Morley	Danielle	Florida Fish and Wildlife Conservation Commission	danielle.morley@myfwc.com

Last name	First Name	Affiliation	Email
Olson	Jack	Florida Fish and Wildlife Conservation Commission	Jack.Olson@myfwc.com
Phillips	Myles	Wildlife Conservation Society	mphillips@wcs.org
Pitt	Joanna	Bermuda	jpitt@gov.bm
Roa	Camilo	Florida International University	croa@fiu.edu
Rowell	Timothy	NOAA Fisheries Northeast Fisheries Science Center	timothy.rowell@noaa.gov
Russell	Martin	SCRFA	martinrussell99@gmail.com
Scharer	Michelle	HJR Reefscaping	michelle.scharer@upr.edu
Semmens	Brice	Scripps Institution of Oceanography at UCSD	semmens@ucsd.edu
Semmens	Christy	REEF	christy@reef.org
Souza	Philip	Univ. of Texas	philip.souza@utexas.edu
Taylor	Chris	NOAA National Ocean Service	chris.taylor@noaa.gov
Thompson	Charles	NOAA Fisheries Southeast Fisheries Science Center	charles.h.thompson@noaa.gov
Tuohy	Evan	Univ. of Puerto Rico	evan.tuohy@upr.edu
Vallee	Richard	Vemco	richard.vallee@innovasea.com
van Kampen	Yuri	Fisher, Bonaire	dahlia.hassell@gmail.com
Welch	Jirani	Bermuda Environment	jpitt@gov.bm
Zayas	Carlos M	Univ. of Puerto Rico	carlos.zayas3@upr.edu

Workshop Steering Committee

Last name	First Name	Affiliation	Email	Expertise
Michaels	William	NOAA	William.Michaels@noaa.gov	Advanced survey technologies
Demer	David	NOAA	David.Demer@noaa.gov	Acoustics and optics
Heppell	Scott	OSU	Scott.Heppell@oregonstate.edu	Spawning behavior, population dynamics
Heyman	William	LGL	wheyman@lgl.com	Cooperative research, FSA conservation
Erisman	Brad	UTEXAS	berisman@utexas.edu	Spawning behavior, FSA assessments
Semmens	Brice	SIO/UCSD	semmens@ucsd.edu	Spawning behavior, population dynamics
Chérubin	Laurent	FAU/HBOI	lcherubin@fau.edu	Oceanography, autonomous platforms, acoustics
Karnauskas	Mandy	NOAA	mandy.karnauskas@noaa.gov	Population dynamics
Scharer	Michelle	HJR	michelle.scharer@upr.edu	FSA assessments, passive acoustic monitoring
Taylor	Chris	NOAA	chris.taylor@noaa.gov	Acoustics, mapping
Gittings	Steve	NOAA	steve.gittings@noaa.gov	Marine sanctuaries, conservation
Nemeth	Rick	UVI	rnemeth@uvi.edu	FSA ecology and behavior
Campbell	Matthew	NOAA	matthew.d.campbell@noaa.gov	Fishery assessments, optical surveys
Caillouet	Ryan	NOAA	ryan.caillouet@noaa.gov	Fishery assessments, optical surveys
Acosta	Alejandro	FL FWC	Alejandro.acosta@myfwc.com	Fishery assessments and management
Glazer	Bob	FL FWC	bob.glazer@myfwc.com	Fishery/conch assessment and spawning area conservation

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

National Oceanic and Atmospheric Administration
Neil A. Jacobs, PhD, Acting Under Secretary
for Oceans and Atmosphere

National Marine Fisheries Service
Christopher W. Oliver, Assistant Administrator
for Fisheries

www.fisheries.noaa.gov

OFFICIAL BUSINESS

National Marine Fisheries Service
1315 East West Highway, SSMC3, F/ST
Silver Spring, MD 20910

View publication stats