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Executive Summary

Ecosystem-based fisheries management (EBFM), a relatively new concept, is a science- and data-hungry enterprise. Given its size and remoteness, the Pacific Islands region (PIR) is particularly data limited. Because of substantial new resources will likely not be allocated to this effort in the near term. Therefore, the authors attempt to outline existing EBF science efforts at PIFSC and highlight some of the more intractable data deficiencies and analytical challenges in our region. We then suggest ways to make meaningful progress toward developing the science needed to advance effective and equitable ecosystem-based fisheries management decisions in the PIR in the face of climate, habitat, ecologic, and socioeconomic changes.

Introduction

In 2016, NOAA Fisheries adopted a policy of ecosystem-based fisheries management (EBFM), "a systematic approach to fisheries management in a geographically specified area that contributes to the resilience and sustainability of the ecosystem; recognizes the physical, biological, economic, and social interactions among the affected fishery-related components of the ecosystem, including humans; and seeks to optimize benefits among a diverse set of societal goals." (NMFS 2016). Put more generally, an EBFM framework strives to build and maintain productive and sustainable fisheries communities, healthy marine and aquatic habitats/ecosystems, and protect threatened and endangered species through an approach that considers multiple jurisdictions, users, disciplines, stakeholders, priorities, and perspectives. NOAA Fisheries identified the following six strategies, each building on the one before, to advance EBFM:

1. implement ecosystem-level planning,
2. increase our understanding of ecosystem processes,
3. prioritize vulnerabilities and risks to ecosystems and their components,
4. explore and address trade-offs within an ecosystem,
5. incorporate ecosystem considerations into management advice, and
6. maintain resilient ecosystems.

To facilitate the implementation of EBFM in the Pacific Islands region (PIR), the Pacific Islands Fisheries Science Center (PIFSC) and Pacific Islands Regional Office (PIRO) conducted a joint EBFM workshop in 2021. The goal was to foster EBFM understanding and improve communication channels between PIRO and PIFSC personnel, better align our execution of research capacity (PIFSC) in support of management mandates (PIRO), and prioritize activities needed to fully implement EBFM in the PIR.

The workshop identified three main areas that require increased focus from both fisheries scientists and managers. First, we need better internal and external communication among NOAA offices and external partners and renewed efforts to engage the communities most affected by our science and management decisions. Second, it is essential to support more focused research efforts to generate data that can be used for multiple analyses, especially in the socioeconomic and pelagic areas. The third area requiring immediate attention is to make our existing data sets and analytical methods transparent and accessible. For all three priorities, sustained fiscal and personnel support are needed to achieve full implementation of EBFM. EBFM requires transformative processes to succeed, and we must recognize that our normal operating procedures and existing funding allocation/prioritization practices will hinder that success.

Status and data challenges for EBF science in the PIR

Science communication among partners and communities

The primary recommendation from the 2021 PIRO/PIFSC EBFM workshop called for improvements to internal and external communication among NOAA offices and external partners, as well as renewed efforts to engage the communities most affected by NOAA science. While PIFSC responds to national mandates and requests from both PIRO and the Western Pacific Region Fisheries Management Council (WPRFMC), our research questions are often more focused on commercial fisheries and protected species at the expense of broader ecosystem considerations and community priorities. Resource allocation decisions rarely encompass the suite of issues facing the PIR that do not fit into these silos. Recent improvements to PIRO/PIFSC communications among a few divisions have led to greater understanding of respective operating constraints and facilitation/funding of particularly relevant ecosystem/habitat research. Our communications with the WPRFMC include ongoing refinements of fishery ecosystem plans (FEPs), regular contributions to Council publications (in particular, stock assessments and SAFE reports), leadership and participation in Council working groups, and limited data sharing. An upcoming EBFM workshop with the WPRFMC, PIFSC, and PIRO will examine ways to expand our cooperative efforts. Our interactions with Hawai‘i and the territories include the western Pacific fisheries information network (WPacFIN), but these efforts are confounded by data uncertainties and process challenges and often constrained by limited resources, opposing priorities and political boundaries that are not recognized by our living marine resources (LMRs). Despite the critical relationship we maintain with the Cooperative Institute for Marine and Atmospheric Research (CIMAR), our research partnerships with academia and non-profits are relatively limited, often by data access and confidentiality concerns. PIFSC lacks comprehensive capabilities to systematically engage our constituent communities in the development and execution of research priorities. Indeed, our understanding of the identity, scope, and scale of our constituent communities is often not well understood, exacerbating the challenge of engagement.

Spatial and temporal scale issues

Field research and data collection efforts in the PIR are limited due to the sheer size of the region. Our exclusive economic zone (EEZ) encompasses over 513 million hectares (5.13×10^6 km^2), 51% of the total U.S. EEZ (Gilman 2007), is spread over 9–12 marine ecoregions (Spalding et al. 2007), and contains LMRs that extend from the intertidal to depths exceeding 11,000 meters. The PIR contains the second-highest number of managed taxa in U.S. regions, including commercial, recreational, and subsistence-valued bottomfishes (e.g., emperors, snappers, groupers), pelagic fishes, crustaceans, corals, and coral reef-associated taxa, the second-highest percentage of stocks of unknown overfished status, and the second-highest numbers of threatened/endangered species (Link and Marshak 2021). The PIFSC lacks spatial and temporal coverage of most of our trust resources. We rely on satellite oceanographic products (e.g., OceanWatch and CoastWatch) for our surface oceanographic and water quality data and have very limited information regarding water mass movements and oceanographic characteristics at depth. Our Protected Species Division (PSD) collects data on endangered and threatened species, with long-term observations and population assessments of monk seals, cetaceans, and sea turtles, with shorter-term data on other species. Our archipelagic research program maintains our longest continual habitat data set (2000–present) but is limited to waters shallower than 30 meters depth, or diver depths. Our only other long-term data collections are PIRO observer data for commercial and non-commercial interactions, and commercial catch data consisting primarily of pelagic tunas and swordfish along with deep-water bottomfish.

The PIR is home to many heterogeneous and dynamic marine environments that manifest at multiple temporal and spatial scales. Regional fisheries scientists struggle to develop research methodologies that account for ephemeral ecosystems and habitats that occur within and outside static state, territorial, and international boundaries, and ways to study mobile fish stocks that populate a three-dimensional ocean environment. Within the EBF science framework, scientists must also incorporate the disparate and culturally distinct Pacific Island fishing and coastal communities that also occur at a variety of scales and contexts. New approaches attempt to integrate the environmentally heterogeneous seascapes of habitats, species' domains, species' interactions, and the socially produced spaces of fishing communities and their local knowledges. These approaches can consider multiple processes at multiple scales, but are constrained by biological, oceanographic, and sociocultural data limitations (St. Martin 2004). Some of the most severe limitations concern localized events that cannot be adequately explained or managed due to disconnects between data collection efforts that typically occur at incompatible temporal and spatial scales.

Spatiotemporal information on distribution of marine fish populations and fishing efforts plays a critical role in conservation and management planning as recent stock assessments and marine resource management move toward an integrated ecosystem approach (Link 2002; Saul et al. 2013). More than 80% of global fish stocks do not have enough data for formal stock assessment (Costello et al. 2012). Spatial and temporal data gaps lead to uncertainty about estimates of abundance and reference points, which may compromise and threaten the ecosystem functioning and socioeconomic processes. Accelerating climate-driven changes in ocean conditions have identified the need for higher resolution spatial and temporal LMR data to address growing uncertainty about resource status and resource managers' need to identify environmentally-informed stock reference points (Tanaka 2019; Pinsky and Mantua 2014; Scuwalski et al. 2016).

Oceanography/climate

A prerequisite for the implementation of EBFM in any region is knowledge of the key environmental processes that influence habitat and LMR population variability. The oceans are experiencing acidification, heating, deoxygenation, stratification, expanding dead zones, sea-level rise, and pollution. Oceanographic and ecological observations of Pacific ecosystems/habitats collected over the last century indicate substantial links among climate processes, oceanographic conditions, and fisheries production. Many of the insights regarding the links between climate variability and LMRs stem from the eastern North and South Pacific, where the oceanographic and ecological sensitivity of coastal and pelagic ecosystems have been relatively well documented. For example, shore-based observations of ocean temperature and sea level along the Pacific coastlines of North and South America that were coupled with fisheries landings data and early monitoring of plankton enabled marine scientists to resolve the ecosystem responses to El Niño, presently recognized as the largest source of ocean-atmosphere variability along much of the equatorial Pacific and the western coastlines of the Americas. In the central Pacific, Woodworth-Jefcoats and Wren (2020) were able to develop environmental predictors for recruitment of bigeye tunas, but such metrics are just beginning to be incorporated into pelagic stock assessments and management (Sculley et al. 2018).

Unlike many other areas of the U.S. EEZ, the large marine ecosystems of the PIR span equatorial to subtropical latitudes. Targeted fisheries in the region rely on many populations that are cosmopolitan in their distribution, and evidence suggests that some individuals cross the basin multiple times in their lives. This means that the oceanographic conditions to which these populations respond can include variability in the complex zonal currents along the equator, mesoscale variability in the subtropical gyres, and changes along the major fronts at the boundaries of these regions. Contrary to the west coasts of the Americas, the expanse of the PIR includes pelagic oceanographic systems that exhibit hydrographic responses to El Niño-Southern Oscillation that are opposite in sign. Large portions of the PIR are strongly affected by other large scale variabilities such as the Pacific Decadal Oscillation and extreme events that are increasing in frequency and strength affecting PIR ecosystems. Together, the vastness of the region and its large pelagic habitats, the diversity of its oceanographic conditions, the broad distribution of many of its species across multiple domains, and the relatively sparse temporal and spatial observations challenge the development of conceptual depictions of the most influential modes of oceanographic and ecosystem/habitat variability.

Current sampling levels are inadequate to provide regional fisheries scientists' the data needed to accurately represent biological and physical conditions at depths and periods relevant to EBF science. With few exceptions, we lack both data and proven analytical methods needed to develop meaningful indicators that can enable dynamic responses to unforeseen events. Many PIFSC scientists have expressed concern regarding our response to these deficiencies since climate change will likely result in greater uncertainty in the projected abundance and distribution of marine trust resources.

Habitat

The presence and health of various habitats are key components of EBF science. Habitats can be described simply as where LMRs live, grow, and procreate; they include the mosaic of environmental conditions that influence the spatiotemporal distributions of LMRs throughout their life stages. We currently lack adequate environmental and biological data at the proper temporal and spatial scales to develop a comprehensive understanding of habitats that are critical to most of our LMRs. Due to the sheer size of the western and central PIR, habitat-based science using available data streams continues to suffer from many deficiencies (e.g., sparse fishery-independent data for species beyond nearshore waters; distribution and abundance of living resources relative to habitat types; lack of size, stage, or age composition data). We need a great deal of foundational data to fully understand and better define Essential Fish Habitats (EFH) and species-habitat relationships, including vital rates, natural mortality, catchability, and movement. These data will enhance the efficacy of EBF science and meet EBF management needs. We particularly need to improve our understanding of habitats and LMR relationships at management-relevant spatiotemporal scales. Our lack of data related to habitat condition and health metrics including physical habitat variables and their influence on LMRs, benthic and water column characteristics at multispecies levels, the ecological connections between species and habitats throughout life stages, and the linkages between inshore and offshore habitats impair our ability to provide sound EBF science information.

Multi-species stock assessments

One of the defining features of EBF science is the incorporation of multiple species interactions into fisheries assessments. Across the spectrum of models available to inform EBF science, multispecies assessment models can be classified as having intermediate complexity ("Models of Intermediate Complexity for Ecosystem assessments" (MICE)). These models are generally chosen when the population dynamics of the species of concern are strongly influenced through trophic interactions and trophically mediated interactions between fisheries. MICE fall somewhere between traditional single-species stock assessment models and whole-ecosystem models, with population dynamics assessed simultaneously with mortality. Mortality is separated into components; mortality from predator-prey interactions is represented though the functional responses of an assumed form. Decomposing mortality into specific mortality causes such as predation and fishing requires additional data even beyond what is needed in modern data-rich assessments. The most critical data requirements are stomach content proportions averaged annually across stomachs, information that is needed to derive estimates for the parameters that define functional responses by fitting the observed diet composition of each species of interest. Diet data indicate the relative changes in species-specific predation mortality and, under certain assumptions, act as a relative abundance index for prey species. Diet data, along with catch composition information, scientific survey composition information, indices of relative abundance, and other integrated assessments can then be used to inform the parameters which define the system state of the chosen model. PIFSC's Long-Term Assessment of Nekton Composition and EcoTrophic Flow in a Subtropical Habitat (LANCETFISH) project is a fine example of long-term diet research that is currently focused on lancetfish. The LANCETFISH project is an example of how one channel of observational data may provide complementary information useful for other applications. LANCETFISH provides information about the trophic interactions of lancetfish themselves, and by using the lancetfish population as a sampling platform, it can also provide qualitative information otherwise unavailable in a data-poor setting about changes in the relative abundance and composition of the forage community supporting the higher trophic level food web as a whole. This information may be incorporated into MICE, food web, and more complex coupled physical-biological ecosystem model simulations. Even our most informed models face the challenge of an increasing lack of stationarity in many of our marine systems due to climate change.

Fisheries life history

Biological sampling of commercial, recreational, and subsistence-valued fish species for life history research is an important component of ecosystem-based science and management. These samples provide estimates of length at age, growth rates, longevity, aspects of reproduction (size and age at maturity, fecundity, spawning season), and mortality. This information is used as direct input to stock assessments, including assessments that use a data-poor approach. Additionally, life history information is important to local management agencies when setting size limits and closed seasons to protect fish while they are spawning to ultimately increase fish population productivity. Fish life history is expected to change in response to climate change; therefore, providing a baseline of information under current conditions is needed to document and understand future impacts. Modeling current levels of catch while using outdated life history parameters can lead to assessment model instability as the models struggle to align current catch and recruitment with misspecified biological parameters. Keeping pace with changing life history parameters, and perhaps more importantly, understanding the drivers of said change, are fundamentally important to the proper management of commercially exploited species. As management moves to a more ecosystem-based approach, biological processes will become increasingly impactful as the biology and ecology of several trophic levels will need to be understood in order to model more complex multi-species systems.

At PIFSC, the primary means of collecting biological samples for life history research in the U.S. Pacific territories are the Commercial Fisheries Biosampling Programs (CFBS), PIFSC Life History Program (LHP) research surveys, and the American Sāmoa Shore-based research effort. The CFBS, which currently contracts with local environmental services companies, operates in Guam (2009–present) and CNMI (2010–present) and previously operated in American Sāmoa (2010–2016). The American Sāmoa Shore-based research effort is proposed to replace the CFBS in this region; however, it is currently delayed due to the global pandemic. The majority of the samples and information collected through these programs are from commercial fishers. LHP surveys that prioritize sample collections from the less accessible areas of the Mariana and the Samoan Archipelagos are becoming more infrequent. Research surveys in American Sāmoa are currently not feasible due to the small bottomfish management unit species (BMUS) quota.

In the U.S. Pacific territories, work on non-BMUS species (typically shallow-water reef fish) was prioritized prior to 2019, and BMUS have been prioritized since 2020. Research efforts on these species include both ‘field sampling’ (trip-level information such as species composition, and individual fish length and weights) and ‘lab work’ (collection and analysis of biological samples such as fin clips, otoliths, gonads) for life history research. Beginning in 2020, the CFBS switched from haphazard otolith collection to a proportional otolith sampling (POS) design. This change was based on a simulation study examining biases associated with improper sampling designs (Schemmel et al. 2022). The POS approach allows for efficient collection of samples and reduces sampling bias that can occur when selecting samples for age and growth.

Biological sampling of pelagic species (e.g., striped marlin, blue marlin, swordfish, bigeye tuna) captured by the Hawai‘i longline fleet is conducted for LHP by the Pacific Islands Region Observer Program. These samples are part of the International Billfish Biological Sampling program (IBBS) that was developed and is managed by PIFSC LHP. This program collaborates with partners in Japan and Taiwan to collect, process, and interpret biological samples across the north Pacific while establishing and maintaining standardized methods of analyses. This will allow us to identify spatial variability in life history parameters across the north Pacific and lays the foundation for future temporal analyses as climate change impacts species biology and distributions.

The overwhelming challenge to life history research is sample collection. The CFBS and IBBS recently adopted the POS sampling design which resulted in cost and time efficiencies of these fishery-dependent programs. However, recent research found that exploitation, specifically of deepwater snappers, results in life history estimates that are different from those of unexploited populations (O'Malley et al. 2019). This can lead to an inaccurate portrayal of fish production in the exploited areas which would then lead to stock assessment model misspecification. Hence, biological samples from unexploited areas are required to put the estimates from exploited areas in the proper context. Samples from these areas are also necessary for LHP climate change research. These samples allow examination of latitudinal gradients (a proxy for temperature) to determine plasticity in life history traits and the impact of temperature as a function of metabolism on those traits. This provides insights into how BMUS and non-BMUS will respond to climate change. However, these samples are not easy to obtain and cannot be collected from commercial fishermen. Research surveys on federal or contracted ships are the only means to collect these samples. Acquiring time on federal ships and securing funding to charter ships is a real and growing challenge (Peterson et al. 2021).

The international nature of projects such as IBBS which focus on pelagic fish research, necessitates the sharing of samples from outside fisheries. In addition to external sample sharing, collaborative meetings and workshops focused on analysis, and processing best practices are required to mitigate sampling and processing effects on estimated life history parameters. The establishment and running of such collaborative efforts are costly and time consuming, but essential to both developing best scientific information for these species as well as providing baselines to understand the effects of continued climate change on pelagic species.

Protected species

Protected species present a particular challenge to EBF science and management in the PIR due to their appearance as unintended bycatch, increasing interactions with near-shore ocean users, potential depletion of prey items, and the rapidly increasing loss of suitable nesting and birthing beaches. While the population statuses of some PIR protected species (including monk seals, certain cetaceans, and sea turtles) are relatively well-known (with notable exceptions such as false killer whales and threatened shark species), the physical and biological features (PBFs) that compose critical habitats in either the pelagic or coastal environments are not. This impedes our ability to identify areas in either the open ocean or the near-shore regions that exhibit those characteristics (e.g., food preference/availability, water temperature, currents, freshwater outflows, shelter from predators) that are necessary for individual and population success. This lack of knowledge makes it difficult to determine what features are coincident with those that certain targeted fish species prefer and inhibits our ability to limit potential incidental bycatch of sea turtles and cetaceans. As climate changes continue to occur, the features that may have defined an area as critical habitat may already have changed, thus making the area no longer favorable for some protected species, e.g., sea turtles. This situation forces us to define critical habitat based on arbitrary threshold numbers of sea turtles present in a near-shore area. A lack of data precludes us from using the same approach for pelagic areas.

Hawaiian monk seals maintain an iconic status in Hawaiʻi as the only endemic marine mammal in the state. With just ~1,400 individuals remaining in the population (Carretta et al. 2021), they are listed as endangered under the ESA and as depleted under the MMPA. A long-term population database (Johanos 2019a, b, c) provides an excellent foundation for population assessments as well as studies of basic biology (Baker et al. 2014), vital rates (Baker and Thompson 2007), and survival threats of Hawaiian monk seals (Baker 2008; Gobush et al. 2017; Gobush and Farry 2012; Harting et al. 2021; Henderson 2001; Johanos et al. 2010). A variety of logistically complex and resource intensive survey methodologies are needed for accurate population surveys (Baker et al. 2006a, Baker 2004; Harting et al. 2017). Even if remote technologies can be employed to supplement on-the-ground assessments, personnel are still required for hands-on recovery actions. Terrestrial habitats are essential for monk seal haul out, rest, predator avoidance, molting, and pupping while they use marine habitats for foraging, play and other underwater behaviors (Abernathy 1999; Cahoon 2011; Parrish et al. 2005; Stewart et al. 2006; Wilson et al. 2017b). Our understanding of monk seal habitat needs led to the designation of monk seal critical habitats which include terrestrial areas constituting major haulout areas, preferred pupping and nursing areas, and marine areas encompassing the primary foraging habitat of monk seals (NOAA 2015). While critical habitat is well defined, climate change (particularly sea-level rise) and incompatible human uses pose grave ecosystem threats to low-lying haul out areas (Baker et al. 2006b; Baker et al. 2020). From a broader EBF science perspective, much of the environmental sampling and complex modeling studies required to better understand potential climate change scenarios will require partnerships with climate science experts.

The pressure of climate change makes it even more important to mitigate anthropogenic threats in the main Hawaiian Islands as terrestrial habitat in the main Hawaiian Islands may become increasingly essential to protected species persistence and recovery because it is less susceptible to certain climate impacts (e.g., hurricanes destroying small low-lying islands in the Papahānaumokuākea Marine National Monument). Nearshore recreational fishing gear interactions with Hawaiian monk seals and sea turtles in the Hawaiian Islands are not well understood because there is little information about fishing pressure or recreational fisher practices. Interaction with fishing hooks is common (Gobush et al. 2017) and entanglement in fishing nets poses a particularly deadly threat to monk seals and has become one of the leading causes of death for seals in the main Hawaiian Islands (Harting et al. 2021). Data outlining human fishing practices, target species, and shoreline usage are needed to inform potential mitigation of seal-fisheries interactions, and will require cooperation with state, local, and community groups. Dedicated resources and research to provide more information on less well-studied endangered and threatened species of whales, sharks, and invertebrates are also needed.

Social science and economics

Better integrating robust economic and social science analyses with natural science and management can provide improved management, healthier ecosystems, more reliable seafood, more profitable businesses, innovative interdisciplinary science, and more sustainable communities through more efficient and well informed trade-offs and a better understanding of how Americans value and use marine resources. This emphasis is described as a national approach to 'Human Integrated Ecosystem-Based Fishery Management'[1]. Simply put, EBF science recognizes that people are a part of marine social-ecological systems, acting as both stressors and stewards of the environment while assuming risks and benefits. A suite of social, cultural, economic, and Indigenous community research efforts are used to monitor and understand socio-economic aspects of the Pacific Islands marine ecosystems. Current research focuses on three main aspects of fishing communities: commercial fisheries, markets, and businesses; non-commercial fisheries and community-sharing networks; and culture and tradition in fishing communities[2]. The latter two areas represent non-market economies that play a large role in the lifeways of our region, and present challenges when developing valuation metrics. PIFSC researchers work with stakeholders and local institutions (e.g., universities, NGOs) and agencies to define research questions, collect data, and to understand who uses and depends on marine resources and how their involvement, preferences, and well-being change over time or under different environmental and management conditions. Highlighting interactions and

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[1] https://www.fisheries.noaa.gov/human-integrated-ecosystem-based-fishery-management-research-strategy-2021-2025-executive-summary

[2] https://www.fisheries.noaa.gov/content/economics-human-dimensions

relationships between communities and LMRs, safe sources of seafood, recovery of protected species, and healthy/resilient ecosystems are key tasks.

A lack of staff, time, and fiscal resources dedicated to regular collection of economic and other social science data inhibits this work. Like many EBF science needs, economic cost earning surveys do not receive regular funding support and are conducted on a quasi-regular basis as funds are made available. The irregular intervals at which these data are collected creates challenges in analyses and interpretation. Other types of social science data are even less consistently collected. While we have been able to conduct some insightful in-depth individual studies, comparison across geographic locations or over time typically is not possible given the lack of resources. This can make it difficult to analyze socio-economic data in concert with longitudinal ecological data for socio-ecological models or to understand or predict the effects of ecological change or regulations on the economics of NOAA stakeholders.

Indices of fishery engagement and reliance are now regularly calculated based on landings and economic value for fishing communities in Hawaiʻi and census county division (https://www.fisheries.noaa.gov/national/socioeconomics/social-indicators-coastal-communities). Indices for environmental justice, climate change, economics, and gentrification are also calculated for communities based on secondary data, such as that from the Census or American Community Survey (https://www.fisheries.noaa.gov/feature-story/community-snapshots-tool-provides-insights-hawaii-fishing-communities). These metrics are also summarized as community snapshots. However, these metrics apply to everyone living in a geographic area, regardless of the degree to which they engage with fisheries. Because we have limited demographic information about the fisheries (i.e., characteristics of people who engage in fishing or the fishery supply chain), we are unable to assess how well geographic community information aligns with fishery participants. Therefore, it is unclear if we are providing adequate, equitable access to resources and services, or if we are equitably representing or including all the voices and stakeholders in planning and decision making.

One of the guiding principles of the EBFM roadmap is to maintain resilient ecosystems; evaluating community well-being is the desired outcome for the social side of the system, just as ecosystem-level measures of resilience are metrics for ecological success. Community well-being is not yet defined consistently or clearly across NOAA Fisheries or EBFM work in general. We are working with other line offices and programs in NOAA, including the National Marine Sanctuaries Office, National Coral Reef Research and Management Program, National Estuary Research Reserve System, and Sea Grant to improve our collective approaches to developing appropriate metrics for human well-being. We are also working to improve our representation of culture and Indigenous knowledges as emphasized by a number of recent Presidential policies (Presidential Memorandum on Tribal Consultation and Strengthening Nation-to-Nation Relationships, 86 Fed. Reg. 7,491 (Jan. 26, 2021)); Executive Order 13,985: Advancing Racial Equity and Support for Underserved Communities Through the Federal Government, 86 Fed. Reg. 7,009 (Jan. 20, 2021; Executive Order 14,031: Advancing Equity, Justice, and Opportunity for Asian Americans, Native Hawaiians, and Pacific Islanders, 86 Fed. Reg. 29,675 (May 28, 2021)). Until we are able to assess community well-being, incorporating the composition of the communities served and metrics of success that include non-market economies, we will be unable to evaluate EBFM progress fairly and inclusively.

NOAA’s Integrated Ecosystem Assessment
NOAA formally launched the Integrated Ecosystem Assessment (IEA) program in 2010 with the intent of conducting science needed to support the ecosystem-based approach to management of complex marine and social ecosystems. The Hawai‘i IEA program conducts ecosystem research in support of EBM along the west coast of Hawai‘i Island where oceanic waters abut the coastal environment and host multiple marine habitats including offshore pelagic, deep-water mesopelagic, and shallow coral reefs. West Hawai‘i is also home to Native and local communities with strong connections to the natural environment, engaging in an array of cultural, traditional, and social practices involving marine ecosystems. Multiple federal and state programs have identified West Hawai‘i as a priority region and numerous non-governmental organizations (NGOs) are working to conserve, restore, and manage its ecosystems.

This unique confluence of diverse ocean ecosystems, strong community connection to place, and overlapping federal, state, and NGO efforts help explain why West Hawai‘i IEA has worked for over a decade. Scientific research led by the IEA in support of EBM include the West Hawai‘i Integrated Ecosystem Assessment Ecosystem Status Reports (Gove et al. 2016, 2019), a compendium of ecosystem indicators useful for tracking the status and trends in ecosystem state. Indicators in these reports were largely driven by community engagement that provided key insights into the region’s social-ecological-system (Ingram et al. 2018). This work highlighted the prominence of cultural ecosystem services in the region and the high proportion of ecosystem pressures that are amenable to local management action. These findings also underpinned collaborative research between the IEA and State of Hawai‘i natural resource managers that evaluated the efficacy of reef ecosystem management strategies in West Hawai‘i (Weijerman et al. 2018). This work showed that existing management was insufficient to support continued delivery of ecosystem services and elucidated key trade-offs among various alternative strategies that ultimately contributed to the state’s resource management planning efforts. IEA-led field expeditions have also produced a number of important scientific findings: small-scale ocean features known as surface slicks serve as nursery habitat for early life history stages of over 100 marine organisms, including multiple larval fish and invertebrates from coral reef, epipelagic, and deep-water ecosystems (Whitney et al. 2021); tropical larval fish are surrounded by and ingesting plastics in their preferred nursery habitat (Gove et al. 2019); the discovery and characterization of a unique, deep-water foraging hotspot for cetaceans such as short-finned pilot whales (Abecassis et al. 2015).

The socioeconomic and cultural connections between people and the ocean environment are a hallmark not just for West Hawai‘i, but all communities across the PIR. Residents and visitors alike depend heavily on ocean ecosystems for income, coastline protection, recreation, food-resources, cultural practices, and research and educational opportunities. These deep seated social-ecological connections make the recent declines in marine ecosystem health even more alarming. The cumulative impacts of human activities and climate change on local and global scales are driving potentially irreversible changes to biological communities and ecosystem function. Numerous NGOs, institutions, and agencies such as NOAA are working towards effective and creative solutions to sustainably manage, conserve, and restore ocean health in the PIR. Successful outcomes from these efforts require integrated research that is inclusive of ecosystems and people across all islands in the PIR.

Despite the large number of agencies, institutions, and organizations conducting research in Hawaiʻi, there are large gaps in information and data availability. For example, we know very little about catches from non-commercial fisheries, which are estimated to be far greater than from commercial fisheries (Wedding et al. 2018). Serious data gaps challenge our ability to assess ecosystem pressures and evaluate approaches to mitigate them in Hawaiʻi. These gaps are even more acute in American Sāmoa, Guam, and other island geographies in the PIR. The task of synthesizing and producing research results at the scale of the entire main Hawaiian Islands (and other PIRs) is daunting but not insurmountable. Developing and maintaining strong and diverse collaborative partnerships alongside transparent data and information sharing has served as the backbone to previous IEA efforts and successes. These core principles will continue to be critically important as the program expands geographic focus beyond West Hawaiʻi.

Data science

Existing data are inadequate to meet the current or future demands that will be placed on PIFSC scientists. The overall status of key commercial and untargeted bycatch species in our multispecies fishery remains uncertain, and there is an urgent need to improve this information in the face of climate change and stakeholder doubt regarding the need for and effectiveness of fishing restrictions. No matter the sophistication of our established models or approaches, they can only reflect the quality of the underlying data. While it may be possible to better utilize existing historical data sets, these data are often unusable due to lack of adequate metadata and survey cross-calibrations. Other data have been collected at limited spatial or temporal scales and do not provide enough information to answer the particular scientific question or management need. Examples include the lack of seasonal biological observations by our coral reef or our pelagic fisheries research programs. Some data are collected using artificial boundary constructs that match neither environmental conditions nor fisher behavior (e.g., State of Hawaiʻi reporting grids). Overall, we lack the data to constitute geographies of variability based on environmental and social seascapes that could serve as a spatial frame for both sampling and analyses (St. Martin 2004).

Over the last few years, PIFSC has successfully made all of our contemporary data collections Public Access to Research Results (PARR) compliant and documented the metadata that facilitates universal discovery. Though the data are available, PIFSC has much work to do regarding transparent and universal access to these and our other public archival data that could encourage and enable more productive partnerships.

EBF science is place-based and requires better spatial data to understand the complex processes that constitute and motivate ecosystems and communities and more comprehensive data collection methods, storage, access, and processing systems, analytical approaches, and computing infrastructure to support our scientific endeavors and community partnerships. A well-designed geographic information system (GIS) could meet many of these needs, but our current GIS infrastructure is inadequately maintained, and many of our data sets are inaccessible/ unusable in their current form to anyone aside from the person who collected them. Our current data policies and standards may be barely adequate for internal use and lead to extreme data silos in each PIFSC division. Many of our analytical methods are not optimized for transparency and collaboration. Our server and cloud computing infrastructure are inadequate to handle the flood of observations from multiple instruments, the data-intensive requirements of the latest modeling techniques, and are unable to store or process increasingly large climate and earth system model outputs, which are essential for projecting the effects of future environmental change on our region's ecosystems. Operations in the Federal Information Security Modernization Act (FISMA)-controlled cloud" require substantial IT support and therefore training of a cloud-capable IT staff. We also lack regional capacity for downscaling climate and earth system models, although the hope is that the NOAA Climate Ecosystems Fisheries Initiative (CEFI) will address this[3] (Peterson et al. 2021; Woodworth-Jefcoats et al. 2021).

Ways forward hindered by resource limits

Communications, collaborations, and agency priorities

Ecosystem-based fisheries science and management require improved communication and collaboration, both internally and with external partners, to facilitate the work of scientists and effectively engage our critical partners. PIFSC must demonstrate its commitment to EBF science by establishing effective and transparent avenues of communication with various stakeholders and communities to incorporate their concerns and expertise into our science priorities and research endeavors.

Communication strategies must be tailored to our various constituencies. Some can be as simple as regular meetings among internal PIFSC divisions, between PIRO and PIFSC divisions, or with outside government agencies that share similar mandates. Alternative forms of enlisting contributions and feedback may be required to deal with state or territorial agencies, non-profit organizations, or academic institutions, but most of these entities do have some research and data infrastructure already established. Communications designed to elicit community input and collaboration will require careful thought and sustained effort. These groups represent diverse and often diametrically opposed interests (e.g., commercial fishers vs. subsistence fishers), and worldviews that are difficult to reconcile with market-based economies and dominant research approaches that often do not consider community priorities and time horizons. NOAA has made a long-term commitment to develop appropriate approaches and partnerships to include these communities transparently and reciprocally in the development of EBF science. This cooperative approach should not only generate more positive community responses but may also provide a labor pool for citizen science and traditional information that is often inaccessible.

Some suggested strategies include:

PIRO/PIFSC Strategy - Formal quarterly discussions and engagement between the PIFSC Ecosystem Sciences Division and the PIRO Habitat Conservation Division provide specific advice to PIFSC scientists regarding PIRO science needs and clarified PIFSC science capabilities to PIRO. EBFM side meetings offer progress reports and/or challenges, highlighting areas for improved collaboration throughout PIFSC and PIRO. Regional senior leadership receive at least annual updates so they can incorporate EBFM into annual guidance plans and highlight EBFM successes to headquarters.

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[3] https://www.fisheries.noaa.gov/topic/climate-change#climate,-ecosystems,-and-fisheries

WPRFMC Strategy -PIFSC continues to work with the Western Pacific Regional Fishery Management Council to include EBFM discussions during Scientific and Statistical Committee (SSC) and plan team meetings. Education efforts among PIFSC/PIRO/WPRFMC provide Council staff and Council members background and attempt to facilitate Council progress regarding Fishery Ecosystem Plan (FEP) updates that incorporate this new approach (the WPRFMC was the first regional council to adopt FEPs). Currently, annual SAFE reports provide an abbreviated version of ecosystem status reports. The Council is aware of and concerned about ecosystem changes and our (in)ability to identify and monitor those of greatest impact. Transparent and simple access to non-confidential PIFSC research data is a Council priority.

The WPRFMC also serves as a venue for communications among the state of Hawaiʻi, the territories of American Sāmoa, Guam, the CNMI, the commercial fishing community, and other stakeholders interested in living marine resources issues. The Council processes provide an existing mechanism for stakeholders to have a voice in EBFM implementation and can serve as a public forum to encourage input on EBFM agenda items.

Interagency and Intergovernmental Strategy: For an EBFM approach to succeed in the PIR, PIFSC needs to meaningfully engage with our federal, state, and territorial partner agencies. Connections with the U.S. Fish and Wildlife Service (USFWS) include our shared interest in marine national monuments and climate change. Hawaiʻi and the U.S. Pacific Island territories rely heavily on PIFSC for data, scientific expertise, and resources. Prioritizing discussion of EBF science and management within the existing interagency communications structure will not only spotlight ongoing EBFM work at PIFSC and PIRO, but more importantly highlight the need for our respective partner agencies to be active collaborators in our work. Informational workshops/briefings to provide common vocabularies and clarify respective roles in this process should commence this year, with periodic progress reports to follow.

Community Engagement Strategy - Effective EBF science and management requires a fundamentally different way of thinking about engaging with communities and partners, with programs that are centered around community-determined needs and co-managed solutions. Engagement strategies that merely solicit input regarding a government-developed plan will not achieve the desired outcomes. PIFSC must develop new methods and cultivate existing relationships that are designed to solicit active community participation that begins with problem identification and continues through collaborative research design and implementation, transparent data archive, access, and analysis, and ends with equitable policy implementation. These approaches provide explicit consideration of ecological and socioeconomic factors directly into science and management efforts. The best community-based programs legitimize and incorporate different forms of local knowledge, lead to more sustainable and equitable solutions, and provide resources needed to address area-based research and enforcement challenges. They allow heterogeneous communities to develop programs that reflect their world views, generate and own localized data, and create communities of practice that may last multiple generations. This concept of collective management is further developed in other studies[4] (Gibbs 2008; National Academies of Sciences, Engineering, and Medicine 2016). See Leong and Decker (2020) and Leong et al. (2009) for a spectrum of stakeholder engagements.

[4] https://esajournals.onlinelibrary.wiley.com/toc/15409309/2016/14/3

Modeling and key trophic interactions

Despite the limited biological and oceanographic data available, development of robust, consistent, and transparent ecosystem models will be a key component to the successful implementation of EBF science. Ecosystem modeling addresses two EBF science and management needs: (1) to supply informed estimates where observational data are desired but absent, and (2) as a tool to explore alternate environmental conditions and management action scenarios. Coupled physical/multi-trophic biological models have been developed to estimate species spatial distributions, productivity, and age-class and size-class distributions. Food web models help predict climate-driven ecosystem change, including projections of how climate change and fishing pressure may interact. More complex end-to-end, physics-to-fisheries models include the socioeconomic and cultural responses to variability and change in environmental conditions, fishing pressure, and other anthropogenic stressors. The more sophisticated end-to-end models incorporate dynamic feedbacks from socioeconomic responses to modify the state of the biological system. One example is the Atlantis model of the main Hawaiʻi Island archipelago ecosystem (Weijerman 2020), and similar models representing the oceanic epipelagic and mesopelagic ecosystem are currently in development.

As with the intermediate complexity multispecies assessment models discussed previously, large-scale ecosystem models are data-hungry, but they may also rapidly become expensive in terms of computation infrastructure requirements. However, development of useful and robust end-to-end ecosystem models can be strategically incremental. Informative models of low and intermediate complexity can be built at levels of spatial and taxonomic resolution and represent processes appropriate to currently available data. More complex models can incorporate additional processes (e.g., diel vertical migration, dynamic foraging behavior, and socioeconomic feedbacks) as our knowledge and observational abilities improve.

Regardless of complexity, meaningful application of ecosystem models should be guided by a defined set of best practices to evaluate the utility and reliability of model-derived metrics. Models can be used to evaluate specific species reference points within a multi-species ecosystem context. Such evaluations can assess the ability of the reference point to maintain operational stock and economic targets over a specified number of decades. Models may also be used to generate reference points of status for entire ecosystems following the example Buchheister et al. (2017). Ecosystem-level reference points may include productivity of indicator species, economic returns of different fishing sectors, and metrics of ecosystem structure such as transfer efficiencies from plankton to pelagic fish, changes in epipelagic and mesopelagic food web scale, fish community size structure, changes in recycling rates, and changes in habitat spatio-temporal variability. The usefulness of ecosystem status metrics may be evaluated in terms of their ability to quantify the trade-offs between competing resource management and conservation objectives (Ruzicka et al. in prep)

The evaluation of model skill (its ability to represent real-world processes and dynamics) in data-poor ecosystems is particularly challenging. However, skill may be effectively evaluated from available observations of fishery yield and CPUE with recognition of two important caveats. First, objective evaluation model skill will be limited by the location and timing of fishing effort. Second, the time-horizon over which model skill must be evaluated will necessarily become longer for metrics involving the higher trophic level groups that are targeted by fishing fleets as these will have longer generational response times.

PIFSC should develop best practices for ecosystem model applications in data-poor regions in cooperation with its partners, NGOs, and other nations that fish and share data in the PIR. A shared framework of best practices would be particularly useful for PIFSC which oversees a large region where resource management requires the cooperation of many partners, both domestic and international.

Remote sensing and uncrewed systems

Using traditional sampling methods, most ecosystem components of the Pacific Islands region will remain critically under-sampled due to the large size and remoteness of the area. The large range of observations at multiple spatiotemporal scales needed to characterize the processes affecting/defining ecosystems also presents extreme challenges to EBF scientists. Satellite and aerial remote sensing along with uncrewed marine systems (UxS) can complement, and in some cases, replace traditional sampling methods and provide the needed observations to potentially fill existing data gaps.

While satellites continue to provide extremely valuable data on surface and near surface ocean temperatures, bathymetry, chlorophyll, turbidity, currents, sea levels, gravimetry, biogenic features (coral reefs), and enable tracking of tagged organisms, new UxS instruments can measure and monitor ecosystem conditions and processes in critical subsurface habitats over a wide range of spatiotemporal scales. Fishery-independent data needs include temperature, salinity, density, current velocity and direction, oxygen, chlorophyll, pH, pCO_2, phyto- and zooplankton distribution and relative biomass, size-distribution, distribution and composition of micronekton, and adult and juvenile species of interest. Multiple types of UxS (saildrones, gliders, etc.) are currently used or under development/testing for use by PIFSC researchers and should enable us to overcome some of our most pressing data needs at a relatively lower cost. The ideal systems would collect a variety of environmental data, be at least semi-autonomous, have relatively long life spans to facilitate extended deployments, and be less expensive than manual data collection efforts.

PIFSC scientists currently utilize a broad array of remote sensing technologies to both make core observations and to place those observations into their environmental and ecological context. This often amounts to pulling relevant environmental variables like temperature and ocean color from available satellite data, pairing these observations with some aspect of fishery-dependent or in situ survey data, and building quantitative models to better understand patterns present in the data. While this approach can provide powerful insights for those fishery-independent survey data that are spatially explicit, the spatial disconnects discussed earlier remain particularly challenging.

ESD has deployed multiple instruments to measure coral reef oceanographic environments for over 20 years. They are currently experimenting with a range of aerial and subsurface imaging devices and analytical methods to enable change detection at multiple temporal and spatial scales. PSD currently deploys many uncrewed aerial systems (UAS) for protected species research, using aerial photographs to determine abundance and reproductive output, population/individual health status, and habitat condition. PSD seeks to utilize UAS more in the future in areas that are difficult to access to supplement survey capabilities; they are also interested in developing methods to accurately estimate body size and condition using photogrammetry. UAS technology could also be used to facilitate the evaluation of sea turtle nesting on unmonitored or isolated beaches in the PIR, ocean surface surveys of in-water turtle densities or important habitats, and surveys of peripheral beaches from primary research beach/camp in the NWHI to quantify basking turtles and female nesting pits, as well as identify individual animals (i.e., via shell etch visualization). PSD is actively upgrading their current uncrewed aerial capabilities with new instrumentation, but additional training will be necessary prior to piloting new drones.

PSD continues to deploy multiple types of acoustic monitoring devices to both fixed locations and to longline fishing sets to cost-effectively monitor and understand protected species habitat locations and interactions with the Hawaiian commercial longline fishing fleet. (Allen, et al. 2022; Merkens et al. 2019; Merkens et al. 2021; Wiggin and Hildebrand 2007; Bayless et al. 2017). PSD also deploys passive acoustic gliders and drifting hydrophones to survey cetacean species in inaccessible areas and hope to use these data to estimate populations density (McCullough et al. 2021a, 2021b). New satellite devices would track the drifters while at sea, and improvements to battery life and greater data storage capacity would extend deployment times. Passive acoustics instrumentation and data such as sound traps and customized-animal-tracking-solution (CATS) tags are playing an important role in the evaluation of soundscapes and their effect on protected species behavior.

ESD and PMEL are currently exploring the use of two Saildrones in the subtropical and tropical central pacific equipped with EK80 and ADCP systems to determine the value and feasibility of combining environmental and acoustic backscatter data to improve model performance in predicting ENSO events and to investigate the acoustic backscatter in response to changes in environmental conditions. Learning about the distribution and relative biomass and composition of scattering layer organisms, mainly micronekton, provides us much needed information in this severely data-poor region. Most Saildrone data (temperature, salinity, chlorophyll, O_2 , and pCO_2) are limited to the surface, with the exception of information on micronekton (EK80) and current (ADCP) vertical profiles to about 1000 m. These data will also be used to investigate changes in micronekton characteristics from waters in the subtropical gyre and in waters of the equatorial current system.

FMRD, PSD, ESD have all deployed various types of satellite tags to explore animal movements and habitats used by various managed species (Abernathy 1999; Cahoon 2011; Littnan et al. 2006; Stewart et al. 2006; Wilson et al. 2017b; Martin et al. 2018; Balazs et al. 2017). Satellite telemetry often provides a broader picture of migration and habitat use and can identify environmental conditions that may create areas of conflicting uses. Telemetry data can be used to identify separate populations (Baird et al. 2009, 2013b), areas of high use (Baird et al. 2012, 2013a; Hill et al. 2019), and in combination with environmental data offer greater insight into cetacean habitat use (Abecassis et al. 2015; Owen et al. 2019). This is key for conservation issues and understanding potential effects of climate change. More extensive deployment of tags with satellite transmission capability requires particular capabilities/expertise and well-designed deployment and data utilization plans and would probably be most successful through development of active partnerships.

PSD has deployed animal-borne cameras (CritterCam, CATS) which provide an excellent view of underwater behavior and habitat use (Parrish et al. 2000; Parrish et al. 2002; Littnan et al. 2004; Parrish et al. 2005; Parrish and Littnan 2007; Parrish et al. 2008; Wilson et al. 2017a).

Triaxial accelerometers provide additional information on foraging movements (Robinson et al. 2021; Wilson et al. 2017a). These biologging data sets have been made publicly available through the Animal Telemetry Network, providing a curated data source for future study of protected species habitat use (e.g., monk seals, Robinson et al. 2020). SOD currently deploys the MOUSS system for deep-water bottomfish stock assessments and habitat delineation. It has developed the OceanEYEs crowdsourcing project that uses volunteer citizen scientists to identify Deep 7 species using MOUSS camera data. The accuracy and utility of these data are being evaluated for multiple uses, including education and outreach and training of automated machine learning annotation models.

All of these technologies are vital to the future advancement of EBF science in the Pacific Islands; they can facilitate more efficient and effective use of limited fiscal and human resources and provide coverage of habitats and species that are unreachable and unobservable. Impediments to the broader adoption of these and other advanced technologies include lack of appropriate infrastructure and training, security concerns, and purchasing restrictions that preclude use of cost-effective and capable instruments, and unfavorable weather conditions in our pelagic regions that lead to poor data quality (Vivier et al. in prep). In order to take advantage of the full potential of these new instruments and data streams, we will need to bolster our computing infrastructure and data management/analysis systems and personnel, adapt current systems to incorporate new data streams, embrace opportunities in advanced data analytics, and improve cross-division cooperation. Special attention must be paid to shared use of resources, instruments, and data, as well as improvements to partner and public access to our data and analyses.

Genomics

Genomics may be a key to advancing EBF science in the PIR as genomics techniques are becoming an established part of monitoring and surveys across NOAA and other government agencies as a complement to existing traditional sampling (Goodwin et al. 2020). Genomics approaches like metabarcoding are increasingly being used to measure biodiversity in marine systems, enhancing our ability to survey and monitor the oceans, from single species to whole ecosystems. For example, environmental DNA (eDNA) metabarcoding has the potential to characterize patterns of diversity, community structure, and relative abundance of communities including species and habitats that are under-surveyed and poorly understood. eDNA metabarcoding can identify entire communities of organisms from microbes to megafauna from single water samples, complementing traditional monitoring methods and providing new ways to detect species missed or under sampled by visual surveys or net samples. PIFSC is embracing emerging genomics tools and assessing the utility of these techniques as a biomonitoring tool to survey marine biodiversity both in the nearshore and pelagic ecosystems.

Nearshore, the West Hawaii IEA program and partners recently conducted a large-scale eDNA survey assessing reef ecosystem biodiversity and relationships with environmental drivers and anthropogenic stressors. This effort coupled eDNA techniques with existing fish and benthic surveys to build composite biodiversity and abundance indices that characterize and inventory the broader ecosystem. The use of multiple assays will facilitate surveying of diverse groups not typically detected by biomonitoring surveys particularly zooplankton, phytoplankton, algae, meiofauna as well as cryptic fish and invertebrates. These under-surveyed groups are important ecosystem components that are likely to respond to environmental gradients (Timmers et al.

2021). If monitored over the long-term, these baselines could help identify key species or even genes that may serve as valuable bioindicators of ecological status and/or ecosystem shifts. This combination of biodiversity indices may enable a more holistic characterization of communities and provide the capacity to scale up biomonitoring across the larger spatial areas relevant to ecosystem-based management (UNIG 2020). The PIFSC Marine Turtle Biology and Assessment Program also uses 'omics techniques to answer questions about demographic structure, mating behavior, breeding sex ratios, and physiological diversity and environmental stressor response of threatened and endangered sea turtle populations within the PIR and serve as subject matter experts within several groups (e.g., Asia-Pacific Marine Turtle Genetics Group and Hawksbill Genetics Group).

The expansive mesopelagic zone is critical forage habitat for tuna and other species supporting the Hawai'i-based longline fishery. It is relatively poorly studied due to technological and logistical challenges of surveying such a large area. The Pelagic Research Program has begun utilizing eDNA metabarcoding to help characterize phytoplankton, zooplankton, micronekton communities that are important parts of ocean's mesopelagic zone and could provide new insight and valuable baselines into the dynamics of pelagic species, including those that are under-sampled or missed by traditional net sampling (e.g., gelatinous zooplankton and net-avoiding fish and squid). eDNA-based analyses coupled with net sampling should enhance resolution of pelagic community diversity and provide us the ability to detect changes in sensitive biological indicators that reflect ecosystem shifts which can be used to inform management strategies (Djurhuus et al. 2020).

In pelagic ecosystems, advances in autonomous underwater platforms fitted with eDNA autosamplers like MBARI's LRAUV-ESP (e.g., Yamahara et al. 2019; Truelove et al. 2022) offer promise to sample marine communities at large spatial scales and for longer-term deployments. This technology could greatly expand the scale of surveys needed to detect changes in biodiversity and ecosystem health in this data-poor region. In complement, moored platforms like those utilized for monitoring harmful algal blooms in the California Current (Moore et al. 2021) could provide continuous and real-time sampling of key bioindicators in habitats not easily surveyable. Given the massive scale of pelagic habitat in the PIR, accessibility of such autonomous vehicles will be critical to improving our surveying capacity both temporally and spatially. However, the current high cost and limited availability of these technologies remain significant hurdles in the short term. Advances in technology and reductions in cost are expected to improve accessibility; institutional investment in building a fleet of such vehicles will be critical to realizing their benefits.

Large-scale eDNA surveys can be cost-effective ways for assessing occupancy and relative abundance of target fisheries, including across life cycles (e.g., eggs, larvae, juveniles) as well as the surrounding ecosystem not currently surveyed by other techniques. Convincing examples of eDNA-derived abundance indices being used to support fisheries management are emerging in other regions (Salter et al. 2019; Fukaya et al. 2021; Shelton et al. 2022). There are certainly considerable limitations and constraints, but the promise is there, at least when applied to single-species surveys using targeted quantitative PCR (qPCR) assays and when sampling error, PCR processes (e.g., amplification bias), and hydrographic conditions are considered (Salter et al. 2019; Kelly et al. 2019; Fukaya et al. 2021; Shelton et al. 2022). In these cases, species-specific assays need to be developed, thoroughly field tested and optimized to ensure sensitivity and reproducibility necessary to reliably detect and quantify target species (Ramon-Laca et al. 2021). In addition, implementation strategies which incorporate genomics-derived indices into monitoring programs and ultimately assessments are still needed.

DNA-based stomach content analyses are valuable tools for unraveling trophic relationships, exploring food web structure and predator/prey relationships of fishery-important and protected species. Metabarcoding of stomach contents can provide high resolution diet composition including identification of prey that would otherwise remain obscure (e.g., degraded, digested prey items). These techniques are embraced in diet studies of pelagic predators like mahi-mahi, bigeye, and swordfish to better understand food web links and constructing marine food webs for monitoring marine ecosystems. When applied to multiple components of the ecosystem, diet metabarcoding can be used to reconstruct diverse and complex trophic webs at high resolution (Casey et al. 2019). If applied over time series, these data sets can detect changes in prey availability and climatic regimes shifts.

Effective genetic identification of species from eDNA or gut contents requires reliable and complete sequence reference libraries. Emerging techniques developed by Hoban (2022) are being scaled-up to make reference sequence generation high-throughput and automated so that large batches of vouchered species can be sequenced, and new reference genomes are added to public repositories rapidly and at scale. These regional efforts to fill gaps in genetic reference sequences are gaining momentum and merging with the wider U.S. Ocean Biocode (Meyer et al. 2021) which seeks to build a comprehensive open-access sequence library of U.S. marine species. Multi-institutional partnerships and long-term sustained efforts to collect and sequence new genetic specimens missing from public databases will be necessary.

If potential for rapid processing and automation are realized, products like eDNA-based indices could provide faster access to monitoring data and thus be utilized to aid assessments in an EBFM framework on quicker time-scales relevant to making operational management decisions (UNIG 2020). Genomics approaches are particularly amenable for use with in situ and autonomous platforms, and thereby offer the promise of continuous and potentially real-time sampling (Goodwin et al. 2020). In the nearshore, development of easily deployable automated samplers will be critical to establishing simplified, reproducible, and scalable eDNA surveys that can be executed across our region and by a wide range of partners, including fishers and citizen scientists. For example, PIFSC is building on a NOAA AOML autosampler design (Formel et al. 2021) that would aid in standardizing large scale surveys in nearshore habitats throughout the PIR.

Citizen Science

PIFSC has neither the resources nor personnel to address all of the data and analysis needs required to effectively perform EBF science and management. The NOAA Citizen Science Strategy (NOAA 2021) provides details on ways “to engage the public in support of key mission areas. Citizen science as well as crowdsourcing, and challenge competitions all provide opportunities for the agency to engage the American public, address societal needs and accelerate science, technology, and innovation. New and emerging technologies, a growing field of practice, and a better connected public are rapidly enhancing citizen science as a powerful tool for research and monitoring.” One of the most important outcomes of our communication and collaboration efforts should be to inform and recruit a cadre of interested people into our science enterprise. NOAA developed a NOAA Citizen Science Action Plan[5] to guide the implementation and application of citizen science across NOAA.

Recent developments in smartphone-based data collection protocols and the growing utilities of cloud-computing platforms provide the potential to transform fishery-dependent data streams in data-poor environments (Global Fishing Watch: DOI: 10.1126/science.aao5646). PIFSC can better utilize commercial and recreational fishers as data sources. One successful example, the California Collaborative Fisheries Research Program (CCRFP)[6], is a voluntary collaboration between anglers and researchers that contributes data to stock assessments and protected area management. The collaborative methodology allows the fishing community to work directly with scientists to provide high quality data, increasing trust and confidence in the resulting data from both groups.

Recruiting and educating a diverse community of participants into our EBF science enterprise would serve achieve goals. Properly trained “citizen scientists” would augment our limited scientific sampling efforts at very fine scales and provide not just new perspectives but possible inroads to previously inaccessible areas and communities. Ideally, these recruits would not just participate in our collaborative science enterprise but also build the trust and networks needed to sustain subsequent management efforts. If successful, such efforts to incorporate community members into our EBF science and management would also advance other NOAA priorities of inclusion, equity, and diversity.

Data to information

EBFM research seeks to integrate and standardize multiple data sources to improve ecological understanding in data poor regions (Grüss et al. 2020). Ecosystem modeling and analyses turn field observations and measurements such as tags, point counts, acoustic data, preferential commercial data, genetic/chemical markers, and local ecological knowledge (Santos et al. 2019; Bender et al. 2014) into information for local, regional, and national fisheries science and management decision-making processes. Input needs for these models and analyses include quantifiable geophysical, biological, and socio-economic data that must be quality-controlled, documented, organized, secured, and made intelligible and accessible. While the past decade has seen an increase in cost-effective quantitative approaches to integrate and standardize multiple in situ measurements while accounting for differences in their sampling protocols and spatiotemporal coverages (Thorson et al. 2021), the PIR lacks the continuous and heterogeneous types of data needed to fully implement EBF science. In addition, our data collection and monitoring efforts are not well coordinated either spatially or temporally. Observation methods among various constituencies lack standardization and calibration. Many data streams are inaccessible and analytical methods are opaque. In order to implement a form of EBF science and management that is inclusive, equitable, and diverse, the PIFSC must develop and use transparent and reproducible systems of data collection and analysis, as well as intuitive and accessible methods of information sharing.

Two complimentary analytical approaches are readily available for use by PIFSC and its partners. One approach that may be most suited for our internal and other government agency

[5] https://sciencecouncil.noaa.gov/wp-content/uploads/2023/04/NOAA-Citizen-Science-Action-Plan_final.pdf
[6] https://www.ccfrp.org/

partners is the use of R, a powerful open-source programming environment for data analysis and modeling. Much of R's power derives from its ease of sharing code, applications, and outputs across a large, engaged community of scientists and resource managers. It has been credited with increasing computational efficiencies and methodological transparencies, maximizing cross-ecosystem data use, and democratizing EBFM applications. Combined with other open-source collaborative platforms such as Github, a new NOAA open science initiative (https://nmfs-opensci.github.io/) supports scientific researchers looking to adopt "reproducible scientific workflows and platforms, facilitate collaboration across offices and regions in shared scientific data science tasks, and support open science, open data and open source communities and initiatives with NOAA Fisheries."

For improved access for non-federal partners, PIFSC could deploy a more fully developed geographic information system (GIS). GIS easily integrates large volumes of georeferenced data (e.g., field observations, imagery, models) in multiple formats from many disparate sources. Its explicit use of location data facilitates place-based analyses and visualizations, and its data management and documentation capabilities are completely compatible with our existing databases. Recent improvements to the software have included the R-bridge (a transparent two-way link to R applications), sophisticated modelling routines, advanced imagery analytics, and incorporation of artificial intelligence and machine-learning algorithms.

NOAA maintains an agency-wide licensing agreement with ESRI, the GIS industry software leader who maintains a huge curated digital map and image inventory (ESRI Living Atlas) that is available to the public. PIFSC has an underdeveloped infrastructure asset called ArcGIS Server, a back-end configurable component of the ArcGIS Enterprise that could make georeferenced PIFSC data and information available to anyone with an internet connection. Through the Server, GIS services allow a server computer to receive and process requests for information sent by other devices, including smart phones. With the development of appropriate apps, Server is able to gather, filter, ingest, and visualize data from multiple sources (and formats), perform real time geospatial analyses, and distribute graphical results in the form of map services with custom-defined capabilities and user interactions. Even if the PIFSC chooses to not further develop our local capacity, NOAA maintains the NOAA GeoPlatform, a cloud-based GIS data, analytics, and visualization platform. NOAA Geoplatform provides access to several key NOAA map services as well as the popular NOAA Story Maps. The site uses ESRI's ArcGIS Online and includes multiple data products and applications that are available to the public for browsing and downloading.

ArcGIS Online is a robust cloud-based mapping and analysis application. It can be used to automate workflows and to access, create, visualize, analyze, and share geographic data and tools online. For EBFM, its greatest feature is its ability to facilitate collaboration among multiple partners with varying degrees of technical capability and computer access. All data, tools, and maps are stored in a secure and private infrastructure that can be configured to meet appropriate access and security requirements. ArcGIS online provides a robust tool to better share data and information with our constituent communities.

Developing MSE-ready science for EBFM

A critical part of EBF science is to evaluate multiple alternatives that can be natural and/or anthropogenic in origin. In well-structured fisheries management systems, clearly defined objectives allow a range of strategies to be evaluated in policy development. These objectives and strategies tend to focus on single species, assuming a degree of stationarity in the underlying state dynamics. Management strategy evaluation (MSE) compares the performance strategies across a suite of metrics in these systems. Ecosystem-based fisheries management (EBFM), an approach that aims to maintain ecosystems in a healthy, productive, and resilient condition so they can provide the services humans want and need, potentially broadens the management objectives for individual fisheries. For EBFM to be considered in an MSE framework, fishery-specific objectives may need to be reframed to contain broader ecosystem considerations as codified by the acts (Magnuson-Stevens Fishery Conservation and Management Act, Endangered Species Act, Marine Mammal Protection Act, National Aquaculture Act, National Environmental Policy Act) that NOAA Fisheries must address. Although specific requirements can be met through a variety of policies, an EBFM approach is intended to be efficient and comprehensive. The challenge is in the implementation of ecosystem-level planning.

At the most fundamental level, an EBFM approach recognizes that the underlying productivity of a stock or population may vary systematically in response to biotic and/or abiotic shifts within its environment. This is an issue of stationary vs. non-stationary productivity. Understanding the difference between natural variability of a population or stock in question versus a fundamental shift in the underlying relationships of that population is an important aspect of EBFM. Causes of these shifts can be categorized as factors that impact the capacity of the environment to support an organism, e.g., its habitat, and those factors that impact the organism's mortality, e.g., trophic interactions. These are often characterized as bottom up and top down forcing. Anticipating the relationship between these factors and the dynamics of the population or stock of interest is the primary challenge of EBFM since these relationships may not have been observed.

Working backwards may help to frame objectives in an EBFM context. This process starts with identifying what is currently managed, identifying the current management objective(s), the policies or strategies that are in place to achieve these objectives, and how the accountability measures (AM) and status determination criteria (SDC) are established. This process alone can be highly instructive but also provides an initial matrix to which EBFM-related questions can be posed. Perhaps some of the most obvious questions are: How are these organisms related? Are ecosystem-related attributes considered in the objective, strategy, AMs, or SDC? Can these links be identified? What tools and metrics are needed to quantify the ecosystem level impacts? Can objectives be reframed to be more amenable to EBFM consideration? Reframing static objectives to those linked to underlying population dynamics facilitates the incorporation of EBFM considerations. These questions should touch on the guiding principles outlined in the NOAA EBFM strategy: implement ecosystem-level planning, advance our understanding of ecosystem processes, prioritize vulnerabilities and risks of ecosystems and their components, explore and address trade-offs within an ecosystem, incorporate ecosystem considerations into management advice, and maintain resilient ecosystems. As the EBFM matrix is resolved at the ecological level, links to social, economic, and cultural impacts should also be established.

Concluding thoughts

One of the premises of this document is that substantial new resources will likely not be allocated to the EBF science initiative. It is obvious that more money would enable the purchase of new equipment, the hiring of critical personnel, and the expansion of ongoing data collection, management, and analysis efforts. Within this document, PIFSC staff have outlined steps that can be taken to overcome some of the challenges to EBF science in our data-limited environment. These steps include improved internal and external communications and collaborations, exploring innovative and unique ways to collect and analyze new observations, more efficiently manipulating existing data and equipment, advanced modeling, and developing more effective and transparent data analyses and sharing capabilities.

We are already working to maximize the application of any available funds. Science center staff have made it a practice to propose a list of "shovel-ready" projects to produce science products which support management priorities. This list is reviewed by our management partners and if projects match current needs, funds are transferred when available. This approach ensures that scientists who best understand the relevant data streams are alerting managers to potential products allowing them to better plan their execution of available resources over time.

However, only so much can be accomplished with the status quo of funding and limited fiscal support for EBF science and management. In this fiscally constrained environment, staff often view demands for resources as a competition rather than a collaboration. Among the many challenges facing EBF science implementation, this may be the most difficult to overcome. A shared vision is essential to filling the largest gaps in our knowledge base, most notably the under-surveyed subsurface seascape of the U.S. Pacific EEZ. Obtaining tools to address this gap means having resources to purchase and operate UxS and UAVs that require specialized training, ongoing maintenance, deployment capability, and data throughput equipment and expertise. While the PIFSC needs to develop better capabilities in this arena, a more realistic approach to some UxS and UAV deployments and surveys may be to form a multidisciplinary assessment team to agree on goals and find capable and willing partners who can shoulder the deployment loads and provide data for a fee. It is also crucial that PIFSC scientists use survey designs that are optimized to collect critical data at the spatial and temporal resolution that is best suited for the particular research question. Ideally, certain surveys might collect data that can be shared among multiple divisions and constituencies.

If EBF science is a priority for PIFSC, leadership needs to make difficult decisions regarding funding for this endeavor. Some new monies may be granted through the NOAA-wide Ecosystem Climate Fisheries Initiative, but they will be limited. PIFSC needs to develop a process through which EBF science priorities are identified and adequately funded. A way forward is for EBF science to augment and make more compelling the multiple analyses conducted to meet NMFS mandates related to habitats, fisheries, and protected resources. Other changes would include

- explicit consideration of targeted and protected taxa, as well as environmental conditions, habitats, and human dimensions;
- minimizing stakeholder disenfranchisement, legal challenges, and negative environmental impacts while optimizing resource extraction;
- rearranging budgets, resources, and organizational structures to support interdisciplinary work;
- establishing protocols and options for management under ocean and climate change;
- improving coordination across management bodies for species shifting their distributions;

- develop methods to measure meaningful perturbations and vulnerabilities to changing climate; and
- developing a suite of dynamic responses to unpredicted ecosystem changes (Link and Marshak 2021).

These integrated analyses offer better support for our partners in PIRO as they conduct regulatory activities such as EFH consultations or NEPA analysis, and at the WPRFMC as they develop fishing regulations. Without additional resources devoted to more than single species management strategies, the PIR will never realize the full potential of EBF science and management.

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