Linking Management of U.S. Caribbean Fisheries to Ecosystem Function

Vinculación de Ordenación de la Pesca Caribe Estados Unidos Ecosistema Funcione

Reliant la Gestion des Pêches Caraïbes aux États-Unis pour le Fonctionnement de L'écosystème

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ABSTRACT

The U.S. Caribbean includes Puerto Rico, St. Croix, St. Thomas, and St. John. These islands support artisanal fisheries targeting spiny lobster, queen conch, and dozens of reef fish species. Effective management of these fisheries, in both state and federal waters, has been challenging due primarily to a dearth of information regarding harvest activities. Population assessments have been attempted (e.g., spiny lobster, queen conch, yellowtail snapper, yellowfin grouper), but none have yielded quantitative management advice. Given the distributed nature of these fisheries, effective management via the assessment process may not soon be achieved. However, other sampling and analytical approaches are available that can be effectively applied to evaluate fisheries sustainability and the relationship of fishing activities to the environment. For example, data-poor approaches (e.g., Spawning Potential Ratio Decision Tree) provide guidance for maintaining sustainable levels of harvest, and genetic approaches can provide complementary estimates of effective population size. When coupled with 3-dimensional physical oceanographic models and biogeographic information, appropriate analyses of genetic data also illuminate source/sink dynamics, the meta-structure of populations and communities, the design and effectiveness of refuges, and sources of resilience. If management actions are taken, environmental indicators need to be in place to provide data necessary to populate before-after-control-impact (BACI) analyses suitable for quantitative calibration of management decisions. Caribbean fisheries are inextricably linked to the ecology of the communities within which they occur. They must be managed within that context, and both economic and ecological considerations dictate maximum efficiency in the utilization of all pertinent data.

KEY WORDS: Indicator, U.S. Caribbean, data-poor methods, fishery management, genetics

BACKGROUND

The United States Caribbean includes the Commonwealth of Puerto Rico and the islands of St. Thomas, St. John, and St. Croix in the Territory of the U.S. Virgin Islands (Figure 1). Recreational and commercial fishing are integral components of the economies of each of these islands, providing $11 million of direct economic impact from the commercial fishery alone (NMFS 2011). Most recreational fishers pursue pelagic species such as tuna and billfish, but an important component of the recreational fisheries and the predominant component of the commercial fisheries derive from coral-reef associated species including a host of finfish and invertebrates (Table 1). To the extent that the harvest of these species occurs in federal waters surrounding each island (Figure 1), the National Oceanic and Atmospheric Administration is responsible for managing harvest under the auspices of the National Marine Fisheries Service (NMFS).

Historically, NMFS' area of responsibility for coral reef associated fisheries has been limited relative to the area of responsibility assigned to Puerto Rico and to the U.S. Virgin Islands. That is because, while the vast majority of the geographic area within the United States exclusive economic zone (EEZ) falls within the purview of the federal government (9 - 200 nautical miles (nm) off Puerto Rico and 3 - 200 nm off the U.S. Virgin Islands), most of the known coral reef habitat and associated fisheries fall within the domain of the island governments (Figure 1). Only about 4.7 percent (116 nm^2 or 398 km^2) of the fishable area is in the U.S. Caribbean EEZ (CFMC 2005). Puerto Rico's state waters comprise an area of approximately 3,832 nm^2 (13,160 km^2) (Puerto Rico Coastal Zone Management Program 2007), and the territorial waters of the USVI are approximately 437 nm^2 (1,564 km^2) in size (Island Resources Foundation 2002). The USVI shelf encompasses an area of approximately 630 nm^2 (2,161 km^2). Of that area, 38 percent (240 nm^2 or 823 km^2) occurs in the U.S. Caribbean EEZ. The bulk of the shelf occurs off St. Thomas and St. John, with 291 nm^2 (998 km^2) of total area in territorial waters and 218 nm^2 (748 km^2) of total area in federal waters. St. Croix has 98 nm^2 (336 km^2) of fishable habitat in territorial waters and only a 21 nm^2 (72 km^2) area off its east coast that resides in the EEZ. It is likely, however, that the degree of federal responsibility will increase as deeper coral reef communities (i.e., mesophotic reefs *sensu* Hinderstein et al. 2010) are discovered and their associated resources identified. Thus, the role of federal fisheries management is destined to increase. Moreover, the relationship between federal and state fisheries management is intertwined via a continuing effort to maintain compatibility in fisheries regulations, linked in process via the Caribbean Fishery Management Council (Council). As a result, while the direct responsibility of NMFS is restricted to federal waters as described above, that responsibility is likely to increase and indirect responsibility via compatibility is a continuing consideration.

The effectiveness of fisheries management in the U.S. Caribbean has long been restricted by a lack of appropriate data with which to conduct species-specific assessments of population health and response to fishing pressure. Among the primary concerns regarding the data are the scarce, missing, or unreliable information on fishing effort, spatial/geographic patterns, and life history parameters.

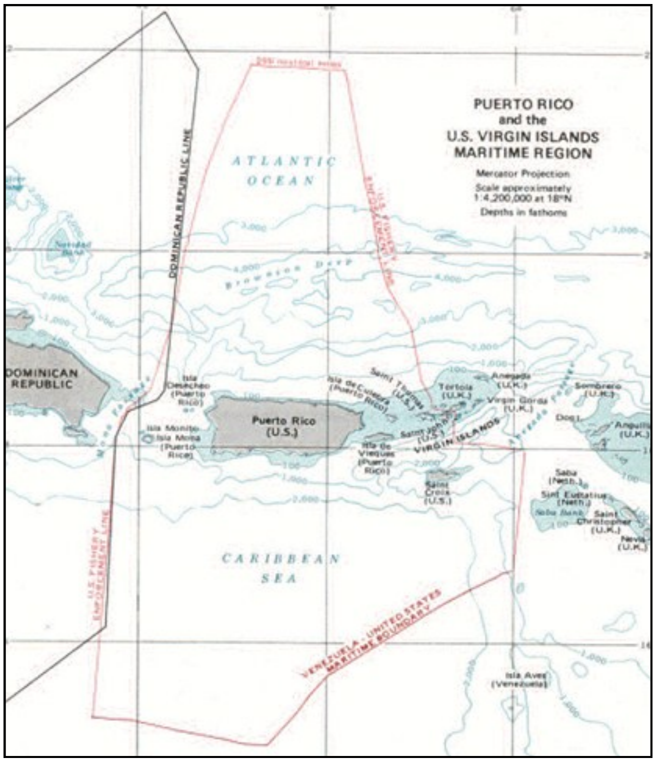

Figure 1. U.S. Caribbean waters including the islands of St. Thomas, St. John, and St. Croix and the archipelago of Puerto Rico. Top-complete map of the U.S. Caribbean exclusive economic zone. Bottom-detailed view of the island groups showing the boundaries of commonwealth and territorial waters relative to the exclusive economic zone.

Table 1. List of federally managed species in the U.S. Caribbean.

REEF FISH FISHERY MANAGEMENT UNIT (FMU)
Lutjanidae--Snapper

Snapper Unit 1
Silk snapper, *Lutjanus vivanus*
Blackfin snapper, *Lutjanus buccanella*
Black snapper, *Apsilus dentatus*
Vermilion snapper, *Rhomboplites aurorubens*
Wenchman, *Pristipomoides aquilonaris*

Snapper Unit 2
Queen snapper, *Etelis oculatus*
Cardinal snapper, *Pristipomoides macrophthalmus*

Snapper Unit 3
Gray snapper, *Lutjanus griseus*
Lane snapper, *Lutjanus synagris*
Mutton snapper, *Lutjanus analis*
Dog snapper, *Lutjanus jocu*
Schoolmaster, *Lutjanus apodus*
Mahogany snapper, *Lutjanus mahogani*

Snapper Unit 4
Yellowtail snapper, *Ocyurus chrysurus*

Serranidae--Sea basses and Grouper
Grouper Unit 1
Nassau grouper, *Epinephelus striatus*

Grouper Unit 2
Goliath grouper, *Epinephelus itajara*

Grouper Unit 3
Red hind, *Epinephelus guttatus*
Coney, *Cephalopholis fulva* (previously *Epinephelus fulvus*)
Rock hind, *Epinephelus adscensionis*
Graysby, *Cephalopholis cruentata* (previously *Epinephelus cruentatus*)

Grouper Unit 4
Red grouper, *Epinephelus morio*
Tiger grouper, *Mycteroperca tigris*
Yellowfin grouper, *Mycteroperca venenosa*
Black grouper, *Mycteroperca bonaci*

Grouper Unit 5
Yellowedge grouper, *Epinephelus flavolimbatus*
Misty grouper, *Epinephelus mystacinus*

Scaridae--Parrotfish
Parrotfish Unit
Midnight parrotfish, *Scarus coelestinus*
Blue parrotfish, *Scarus coeruleus*
Rainbow parrotfish, *Scarus guacamaia*
Princess parrotfish, *Scarus taeniopterus*
Queen parrotfish, *Scarus vetula*
Redfin parrotfish, *Sparisoma rubripinne*
Redtail parrotfish, *Sparisoma chrysopterum*
Stoplight parrotfish, *Sparisoma viride*
Redband parrotfish, *Sparisoma aurofrenatum*
Striped parrotfish, *Scarus iseri* (previously *Scarus croicensis*)

Haemulidae--Grunts
White grunt, *Haemulon plumieri*
Margate, *Haemulon album*
Tomtate, *Haemulon aurolineatum*
Bluestriped grunt, *Haemulon sciurus*
French grunt, *Haemulon flavolineatum*
Porkfish, *Anisotremus virginicus*

Mullidae--Goatfishes
Spotted goatfish, *Pseudupeneus maculatus*
Yellow goatfish, *Mulloidichthys martinicus*

Sparidae--Porgies
Jolthead porgy, *Calamus bajonado*
Sea bream, *Archosargus rhomboidalis*
Sheepshead porgy, *Calamus penna*
Pluma, *Calamus pennatula*

Holocentridae--Squirrelfishes
Blackbar soldierfish, *Myripristis jacobus*
Bigeye, *Priacanthus arenatus*
Longspine squirrelfish, *Holocentrus rufus*
Squirrelfish, *Holocentrus adscensionis*

Malacanthidae--Tilefishes
Blackline tilefish, *Caulolatilus cyanops*
Sand tilefish, *Malacanthus plumieri*

Carangidae--Jacks
Blue runner, *Caranx crysos*
Horse-eye jack, *Caranx latus*
Black jack, *Caranx lugubris*
Almaco jack, *Seriola rivoliana*
Bar jack, *Caranx ruber*
Greater amberjack, *Seriola dumerili*
Yellow jack, *Caranx bartholomaei*

Acanthuridae--Surgeonfishes
Blue tang, *Acanthurus coeruleus*
Ocean surgeonfish, *Acanthurus bahianus*
Doctorfish, *Acanthurus chirurgus*

Balistidae–-Triggerfishes
Ocean triggerfish, *Canthidermis sufflamen*
Queen triggerfish, *Balistes vetula*
Sargassum triggerfish, *Xanthichthys rigens*
Black durgon, *Melichthys niger*

Monacanthidae–-Filefishes
Scrawled filefish, *Aluterus scriptus*
Whitespotted filefish, *Cantherhines macrocerus*

Ostraciidae--Boxfishes 528
Honeycomb cowfish, *Acanthostracion polygonia* (previously *Lactophrys polygonia*)
Scrawled cowfish, *Acanthostracion quadricornis* (previously *Lactophrys quadricornis*)
Trunkfish, *Lactophrys trigonus*
Spotted trunkfish, *Lactophrys bicaudalis*
Smooth trunkfish, *Lactophrys triqueter*

Labridae--Wrasses
Hogfish, *Lachnolaimus maximus*
Puddingwife, *Halichoeres radiatus*
Spanish hogfish, *Bodianus rufus*

Pomacanthidae--Angelfishes
Queen angelfish, *Holacanthus ciliaris*
Gray angelfish, *Pomacanthus arcuatus*
French angelfish, *Pomacanthus paru*

AQUARIUM TRADE SPECIES FMU
Aquarium Trade Species listed in the Reef Fish FMP
Frogfish, *Antennarius* spp.
Flamefish, *Apogon maculatus*
Conchfish, *Astrapogon stellatus*
Redlip blenny, *Ophioblennius macclurei* (previously *Ophioblennius atlanticus*)
Peacock flounder, *Bothus lunatus*
Longsnout butterflyfish, *Prognathodes aculeatus* (previously *Chaetodon aculeatus*)
Foureye butterflyfish, *Chaetodon capistratus*
Spotfin butterflyfish, *Chaetodon ocellatus*
Banded butterflyfish, *Chaetodon striatus*
Redspotted hawkfish, *Amblycirrhitus pinos*
Flying gurnard, *Dactylopterus volitans*
Atlantic spadefish, *Chaetodipterus faber*
Neon goby, *Elacatinus oceanops* (previously *Gobiosoma oceanops*)
Rusty goby, *Priolepis hipoliti*
Fairy basslet, *Gramma loreto* (also known as Royal gramma)
Creole wrasse, *Clepticus parrae*
Yellowcheek wrasse, *Halichoeres cyanocephalus*
Yellowhead wrasse, *Halichoeres garnoti*
Clown wrasse, *Halichoeres maculipinna*
Pearly razorfish, *Xyrichtys novacula* (previously *Heminopteronotus novacula*)
Green razorfish, *Xyrichtys splendens* (previously *Heminopteronotus splendens*)
Bluehead wrasse, *Thalassoma bifasciatum*
Chain moray, *Echidna catenata*
Green moray, *Gymnothorax funebris*
Goldentail moray, *Gymnothorax miliaris*
Batfish, *Ogcocephalus* spp.
Goldspotted eel, *Myrichthys ocellatus*
Yellowhead jawfish, *Opistognathus aurifrons*
Dusky jawfish, *Opistognathus whitehursti*
Cherubfish, *Centropyge argi*
Rock beauty, *Holacanthus tricolor*
Sargeant major, *Abudefduf saxatilis*
Blue chromis, *Chromis cyanea*
Sunshinefish, *Chromis insolata*
Yellowtail damselfish, *Microspathodon chrysurus*
Dusky damselfish, *Stegastes adustus* (previously *Pomacentrus fuscus*)
Beaugregory, *Stegastes leucostictus* (previously *Pomacentrus leucostictus*)
Bicolor damselfish, *Stegastes partitus* (previously *Pomacentrus partitus*)
Threespot damselfish, *Stegastes planifrons* (previously *Pomacentrus planifrons*)
Glasseye snapper, *Heteropriacanthus cruentatus* (previously *Priacanthus cruentatus*)
High-hat, *Pareques acuminatus* (previously *Equetus acuminatus*)
Jackknife-fish, *Equetus lanceolatus*
Spotted drum, *Equetus punctatus*
Scorpaenidae-scorpionfishes
Butter hamlet, *Hypoplectrus unicolor*
Peppermint basslet, *Liopropoma rubre* (also known as Swissguard basslet)
Great soapfish, *Rypticus saponaceus*
Orangeback bass, *Serranus annularis*
Lantern bass, *Serranus baldwini*
Tobaccofish, *Serranus tabacarius*
Harlequin bass, *Serranus tigrinus*
Chalk bass, *Serranus tortugarum*
Caribbean tonguefish, *Symphurus arawak*
Seahorses, *Hippocampus* spp.
Pipefishes, *Syngnathus* spp.
Sand diver, *Synodus intermedius*
Sharpnose puffer, *Canthigaster rostrata*
Porcupinefish, *Diodon hystrix*

Aquarium Trade Species listed in the Corals and Reef Associated Plants and Invertebrates FMP (Coral FMP)
Erect rope sponge, *Aphimedon compressa*
Giant basket star, *Astrophyton muricatum*
Snapping shrimp, *Alpheaus armatus*
Pale anemone,, *Aiptasia tagetes*
Sand stars, *Astropecten spp.*
Swimming crinoid, *Analcidometra armata*
Corkscrew anemone, *Bartholomea annulata*
Sponge (no common name), *Cynachirella alloclada*
Giant pink-tipped anemone, *Condylactis gigantea*
Flamingo tongue, *Cyphoma gibbosum*
Chicken liver sponge, *Chondrilla nucula*
Long-spined urchin, *Diadema antillarum*
Crinoids, *Davidaster spp.*
False coral, *Discosoma spp.*
Purple urchin, *Echinometra spp.*
Pencil urchin, *Eucidaris tribuloides*
Smashing mantis shrimp, *Gonodactylus (Neogonodactylus) spp.*
Potato sponge, *Geodia neptuni*
Finger sponge, *Haliclona spp.*
Sea cucumbers, *Holothuria spp.*
Knobby anemone, *Hereractis lucida*
Fileclams, *Lima spp.*
Rough fileclam, *Lima scabra*
Pin cushion urchin, *Lytechinus spp.*
Peppermint shrimp, *Lysmata spp.*
Common comet star, *Linckia guildingii*
Spearing mantis shrimp, *Lysiosquilla spp.*
Staghorn anemone, *Lebrunia spp.*
Clinging crabs, *Mithrax spp.*
Banded clinging crab, *Mithrax cinctimanus*
Green clinging crab, *Mithrax sculptus*
Sponge (no common name), *Myriastra sp.*

Pink vase sponge, *Niphates digitalis*
Lavender rope sponge, *Niphates erecta*,
Crinoids, *Nemaster spp.*
Brittlestars, *Ophiocoma spp.*
Brittlestars, *Ophioderma spp.*
Ruby brittlestar, *Ophioderma rubicundum*
Cushion sea star, *Oreaster reticulatus*,
Comet star, *Ophidiaster guildingii*
Netted olive, *Oliva reticularis*
Octopus (except the common octopus, *O. vulgaris*), *Octopus spp.*
Hermit crabs, *Paguristes spp.*
Red reef hermit crab, *Paguristes cadenati*
Nimble spray crab, *Percnon gibbesi*
Cleaner shrimp, *Periclimenes spp.*
Florida false coral, *Ricordia florida*
Sun anemone, S*tichodactyla helianthus*
Christmas tree worm, *Spirobranchus giganteus*
Magnificent duster, *Sabellastarte magnifica*
Tube worms, *Sabellastarte spp.*
Golden shrimp, *Stenopus scutellatus*
Banded shrimp, *Stenopus hispidus*
Yellowline arrow crab, *Stenorhynchus seticornis*
Atlantic thorny oyster, *Spondylus americanus*
Iridescent tube sponge, *Spinosella plicifera*
Lavendar tube sponge, *Spinosella vaginalis*
Sea egg urchin, *Tripneustes ventricosus*
Anemone shrimp, *Thor amboinensis*
Sponge (no common name), *Tectitethya (Tethya) crypta*
Tunicates Subphylum Urochordata
Lettuce sea slug, *Tridachia crispata*
Sea mat, *Zoanthus spp.*

QUEEN CONCH FMU
Queen Conch, *Strombus gigas*

SPINY LOBSTER FMU
Caribbean Spiny Lobster, *Panulirus argus*

Although some fishery independent data are available, they are spatially and temporally limited and previous assessment efforts have been unable to incorporate a viable time series into the analyses (SEDAR 2009). Fishery dependent data (i.e., landings data) have been collected for Puerto Rico commercial fisheries since the late 1960s (Cummings 2008) and for U.S. Virgin Islands commercial fisheries since 1975 (McCarthy and Gedamke 2008). However, those data have shortcomings that limit their suitability for assessing population status (CFMC 2011a). Until the late 1990s in the U.S. Virgin Islands, data were reported by gear type rather than by species or species group. For St. Croix, data deemed by the Council to be suitable for monitoring landings first became available in 1998. Even from that point, the data are only reported to species group (snapper, grouper, parrotfish, grunts, etc.) rather than to species with the possible exception of Caribbean spiny lobster (*Panulirus argus*) and queen conch (*Strombus gigas*). For St. Thomas and St. John (considered for the purposes of this paper as a single island group), such data did not become available until 2000. Puerto Rico landings data have ostensibly been reported to species throughout the landings history, but even those data are compromised in several ways. First, underreporting is acknowledged to the point that reported landings are adjusted upward on a regional basis by 50% or more to account for this underreporting. Additionally, although catch reporting forms include a long list of species, most fishers report in a more general manner. For example, although ten species of parrotfish may be available for harvest in Puerto Rico waters, only a small percentage (< 1%) of the parrotfish catch is actually reported to species, with the remainder reported simply as ‘parrotfish’ (CFMC 2011a). To complicate assessment efforts further, reporting of biological data related to harvest (e.g., information on age, size, reproductive status) has been limited (McCarthy and Gedamke 2008). Evaluation of approaches to improve that situation are underway, but the anticipated cost required to improve reporting for just the commercial sector of these fisheries is estimated at more than $4 million per year (Harrington and Trumble 2011). Even following initiation of an improved commercial data collection program, it has been estimated that at least a decade of collection will be required before adequate data are available with which to populate suitable assessment models (Todd Gedamke, pers. comm.). Recreational data are also limited. A recreational reporting program (Marine Recreational Fishing Statistical Survey (MRFSS)) was not initiated in Puerto Rico until 2000 so the recreational data stream for that island is relatively short. In the U.S. Virgin Islands, a program to collect recreational catch data is not yet underway although a pilot program was conducted for a single year in 2000.

Another concern with population assessment approaches is that, while they may provide suitable estimates of the abundance and health of individual populations, the relationship between the status of the individual species and the overall health of the coral reef community upon which the suite of harvested species depends is not assessed. For coral reef ecosystems, understanding such relationships is essential to proper management because of the tight linkage between the health of the habitat and the health of the species (Knowlton and Jackson 2001). Extractive activities such as fishing can alter the balance of the coral reef ecosystem in ways that are not always well understood, but fishing activities are commonly cited as a principal threat to coral reefs (e.g., Maragos et al. 1996). Certainly there is resilience within the coral reef ecosystem, but the extent to which that resilience can be maintained in the face of biased and non-evolutionary mortality patterns is not well known. As with all activities that affect the coral reef ecosystem, fishing activities cannot be assessed in a vacuum but must instead be evaluated within the context of ecosystem function.

As mentioned above, the U.S. Caribbean is considered data poor with respect to the information generally acknowledged as being necessary to calibrate and populate assessment models. It is not likely the situation will change in the near future because, as noted above, even when an expanded commercial and recreational data collection program is implemented it will take years to acquire sufficient information for successful accomplishment of species-specific assessments. However, there are opportunities available now that can be applied to address management considerations across a range of applications, including those that provide insights rapidly, efficiently, and at relatively low cost (data-poor assessments) and those that may be longer-term in nature but in many cases are already underway (e.g., genetic, hydrodynamic, biogeographic studies). Such information can be used both to assess the present status of coral reef fisheries and to manage future harvest patterns. Ecological indicators that produce data indicative of a response to management actions can then be consulted to evaluate the success of those management actions and to guide future management strategies.

Data-poor Approaches

A workshop was convened by the Caribbean Council in San Juan, Puerto Rico, during February 22 - 24, 2011, to evaluate various approaches to assessing U.S. Caribbean fishing activities and impacts within a data-poor context. Four general approaches were considered (Table 2) ranging from ecological risk assessment to assessing status via comparisons of population density inside versus outside of marine reserves. All of the methods are designed to operate within the context of limited data and funding, commonly controlling costs by relying on involvement of the fishers to provide necessary data. The Ecological Risk Assessment for the Effect of Fishing (ERAEF) process produces estimates of risk associated with each fishery or sub-fishery within the region, relying upon a multi-tiered approach beginning with a qualitative Level 1 assessment that identifies prominent risks within a stakeholder-driven workshop setting, the outcome of which identifies those components of the fishery in need of more quantitative evaluations. Levels 2 and 3 become increasingly more quantitative and specialized, relying less on stakeholder input and more on data and modeling. The ERAEF approach has considerable value in identifying at-risk fisheries, thereby providing guidance for monitoring and management efforts.

The remaining three approaches (Table 2) analyze monitoring outcomes to provide guidance regarding the relative health of the populations upon which the fisheries depend. They differ primarily in the type and amount of input data, but in all three cases a key output is advice regarding adjustments to annual catch levels. The Density Ratio Control Rule approach is the least demanding with respect to data, utilizing information on the relative density of a species from inside versus outside of well-established marine reserves. Both the Spawning Potential Ratio Based Decision Tree and the Marine Reserve Based Decision Tree are more data intensive, the former using estimates of spawning potential ratio to ensure that reproductive capability is preserved in all sub-populations whereas the latter depends on comparisons of basic biological parameters such as growth and mortality rates between areas open and closed to harvest.

A necessary first step in the process of reducing impacts of fishing on coral reef communities is to end overfishing. The annual catch limit (ACL) process recently completed by NMFS essentially ends overfishing of all species throughout U.S. EEZ waters by constraining levels of annual catch within bounds established for sustainability. The U.S. Caribbean EEZ is no exception (CFMC 2011a, 2011b). However, once the ACLs are established, it is incumbent upon both state and federal managers to both ensure that those catch limits are adhered to via effective monitoring of catch and application of accountability measures as appropriate, and to adjust the ACLs in response to changes in the population or environment that either require ACL reduction or that create opportunities to increase harvest levels within the context of maximum sustainable yield. The data-poor approaches described above provide tools necessary to accomplish these tasks in an environment of limited funds and limited data. These approaches therefore provide an essential contribution to the process of maintaining sustainable fisheries within the context of healthy coral reef ecosystems.

Expanding the Data Landscape for Fisheries Management in the U.S. Caribbean

While ending overfishing within the reef fish fisheries of the U.S. Caribbean is a necessary precursor to rebuilding the health of coral reef communities, it is then important to understand those harvest levels within the larger framework of ecosystem function. Ecosystem function comprises many facets including (but not limited to) the function of the community meta-population, the linkages among the local populations comprising that meta-population, and the distribution and health of essential habitats relative to those linkages. Accomplishing this goal requires expanding the information base to include considerations of genetics, hydrodynamics, and biogeography. However, it does not exclusively require initiating new data acquisition efforts because many studies within these disciplines are already underway or recently completed in the U.S. Caribbean. Those studies represent a substantial investment of time and money, so it is imperative that the resultant data be applied to the greatest degree possible.

Genetic data have numerous applications within the context of fisheries management, including estimating effective population size (N_e), delineating source-sink dynamics, defining gene flow patterns among populations, and describing the range of genetic diversity within a population. From this information can be determined the meta-structure of populations and communities, the design and effectiveness of reserves, and the resilience of a population, which are critical elements in the evaluation and rehabilitation of coral reef communities.

As described by Hare et al. (2011), N_e "*is crucial to management because it integrates genetic effects with the life history of the species, allowing for predictions of a*

Table 2. Matrix of data-poor approaches considered during a workshop convened in San Juan, Puerto Rico during February 22-24, 2011. Table provided by Kim Gordon of the Fisheries Leadership and Sustainability Forum.

Data-poor approach	What does it do?	What management guidance is provided?	What does it NOT do?	What are the input data?	Short-term or long-term strategy?
Spawning Potential Ration (SPR) Based Decision Tree *Jeremy Prince*	Uses an iterative decision making process to adjust catch limits Can be qualitative or data driven	Annual Catch Limit (ACL) Adjustment	Does not give an estimate of biomass or fishing mortality	Size composition data Estimates of SPR based on an extension of the Beverton-Holt Life History Invariance Model	Short-term: can be used in a qualitative form to refine ACLs Long-term: can become more complex with additional data
Marine Reserve Based Decision Tree *Jono Wilson*	Uses an iterative decision making process to adjust catch limits Utilizes fishing mortality and SPR based reference points	ACL adjustment	Does not give an estimate of biomass Does not calculate MSY	Length frequency data from inside and outside of marine reserves Basic life history information (growth, mortality, age or length at reproductive maturity) Selectivity of fishing gear	Short-term: can be used with minimal time series data to refine ACLs Long-term: collects size structure and catch per unit effort data to support stock synthesis models in the long-term
Density Ratio Control Rule (DRCR) *Elizabeth Babcock*	Restrains fishing effort to a level that would be sustainable Uses ratio of densities inside and outside of marine reserves as a metric for the impact of fishing	ACL adjustment Effort adjustment	Does not provide estimates of SPR or other metrics for fisheries management	Monitoring data from inside and outside marine reserves Well established marine reserves Does not require catch data	Long-term: Can manage fishing effort at sustainable levels, without catch data, to achieve target population densities
Ecological Risk Assessment for the Effects of Fishing (ERAEF)	Provides a comprehensive risk assessment and identifies risk-prone stocks Identifies and compiles available data, and highlights data needs Provides an avenue for stakeholder engagement	Identification of high-risk stocks Guidance on how to direct limited resources Comprehensive database Insight into appropriate methods for quantitative assessments	Does not provide ACLs	Level 1: fishermen and expert knowledge Level 2: some biological information and available existing data Level 3: requires quantitative data to support method based assessment	Short-term: provides risk assessment and guidance for management and data collection priorities Long-term: Contributes to ecosystem-based fisheries management

population's current and future viability." N_e is not equivalent to assessed population size and generally is a much smaller value (see Table 3 for example), but its integrative nature better reflects in a relative sense the long-term status of the population. Moreover, its definition as an index of the population being studied to a theoretical ideal population allows for direct comparison of N_e estimates among diverse populations (Carson et al. 2011) or among time points within a single population (Lessios et al. 2001). As exemplified in Table 3, estimates of N_e vary substantially among sites within a population and that variability may be useful in a management context (Hare et al. 2011). The N_e for mutton snapper is much lower in St. Croix than in other sampled populations (Table 3). The significance of that pattern remains to be fully evaluated, but such patterns of N_e variation may provide guidance regarding application of research effort. Estimates of N_e are available for an increasing number of species in Caribbean waters (e.g., Lessios et al. 2001, Hemond and Vollmer 2010, Gold et al. 2011, Carson et al. 2011), so there is a strong need to determine how to effectively and appropriately apply these data within a management context.

Estimates of N_e may be robust enough to stand alone in management applications, but other genetic data such as gene flow rates derived from estimates of F_{ST} benefit from being placed within a context of hydrodynamics and habitat distribution patterns (Galindo et al. 2006, Kininmonth et al. 2010, Costantini et al. 2011). F_{ST} is derived from the inbreeding coefficient and has been used as an estimate of gene flow among populations (Neigel 2002). While F_{ST} as a concept is familiar to most ecologists, new and more robust methods of estimating gene flow among populations are now being used (Neigel 2002, Marko and Hart 2011). Regardless of the method, estimates of gene flow among populations, when coupled with circulation patterns and habitat distributions, provide valuable information on the dynamics of connectivity among populations (Cowen et al. 2007) and on the source/sink relationships among the local populations that comprise the metapopulation (Kritzer and Sale 2006) for that species.

Patterns of connectivity are an important consideration in the effective management of living marine resources (Cowen et al. 2007). Most marine populations, especially relatively sessile species, are structured as metapopulations composed of a network of local populations that are more or less connected to one another (see Kritzer and Sale 2006 for an extensive overview). The vectors of connectivity are commonly, though not always, the larval life stage. Those pathways of connectivity appear to be more complex than previously thought. For example, Caribbean spiny lobsters (*P. argus*) have historically been considered to freely exchange larvae throughout the Caribbean Sea and the Gulf of Mexico. Recent research suggests otherwise, and behavioral characteristics of the larvae may substantially limit their dispersal. Outcomes from a coupled biophysical model predicted that lobster larvae exhibiting ontogenetic vertical migration generally settled < 400 km from their spawning site whereas passive larvae settled > 1000 km away (Butler et al. 2011). Constraints to larval dispersal act not only on the species inhabiting the reef but on the coral species providing the essential reef structure (Baums et al. 2006). Patterns of connectivity, and factors influencing those patterns, are important features of coral reef communities and may be amenable to management efforts (McCook et al. 2009).

With the development of advanced SCUBA techniques, there is increasing awareness of the distribution, abundance, and potential importance of mesophotic coral reef ecosystems throughout the U.S. Caribbean. Mesophotic reefs are those that occur in light-limited situations, generally at depths > 30 m (Locker et al. 2010, Garcia-Sais 2010). It has been hypothesized that these mesophotic reefs may provide a refuge for members of shallow water reef communities that are suffering due to local and global-scale anthropogenic stressors (Bongaerts et al. 2010), although differences in community structure between shallow and deep reefs (Garcia-Sais 2010) suggest that the rescue effect may be taxonomically limited. Results from a genetic study also suggest limited connectivity between deep and shallow reefs for the red coral *Corallium rubrum* (Costantini et al. 2011), and there is evidence that community composition differs between shallow and deep reefs (Kahng et al. 2010). It is evident that mesophotic reefs and the communities they support are common constituents of U.S. Caribbean waters (Locker et al. 2010). It is therefore imperative that the importance of these habitats as sources of recruits for shallow-water reef populations and as sites for commercial and recreational harvest be ascertained and, in the case of harvest activities, that appropriate management regimes are put in place prior to increased exploitation. Again, already available data on the known and predicted locations of mesophotic reefs in U.S. Caribbean waters provide a start point for these initiatives (Locker et al. 2010).

Information on two-dimensional (surface) and three-dimensional hydrodynamic patterns in the U.S. Caribbean are also available. Hydrodynamic influences on larval dispersal patterns may be extremely complex, influenced both by predictable advective processes and by chaotic diffusive processes (Arnold et al. 2005, Hitchcock et al. 2008). Surface-current studies have been integrated with larval fish distribution data (Gerard et al. Undated, Lamkin et al. Undated, Smith et al. 2008) in an effort to predict linkages among spawning sites and settlement sites. Those studies provide valuable information on general biological oceanographic patterns, but a full depiction of larval transport patterns may be limited by the surface oriented nature of these studies relative to the three-dimensional distribution of larval reef fish (Irisson et al. 2010). The importance of a three-dimensional approach to a complete understanding of local-scale larval dispersal patterns is apparent from the work of Cherubin et al. (2011), who showed that surface currents advect larval red hind (*Epinephelus guttatus*) away from the spawning grounds but that many of those larvae are returned within 8-10 days to the vicinity of the spawning site via a combination of downwelling and subsurface currents opposing surface current patterns. Hydrodynamic studies such as these provide valuable information regarding connectivity and the location of source versus sink populations of managed marine species. Those outcomes are directly applicable to siting and management of marine reserves and to the spatial allocation of fishing effort. The latter is of particular importance in a management context because a viable management strategy is to focus fishing effort on sink rather than source populations in an effort to ensure the continued reproductive viability of the population. In that

Table 3. Estimated N_e for populations of mutton snapper (*Lutjanus analis*) from various sites in Florida and the U.S. Caribbean. STX = St. Croix, USVI; STT = St. Thomas, USVI; PRE = Puerto Rico east coast; PRW = Puerto Rico west coast; FL Keys = Florida Keys. See source manuscript for specific sampling locations.

Species	STX	STT	PRE	PRW	FL Keys	Source
Mutton Snapper	341	922	828	646	1066	Carson et al. 2011

regard, it is necessary to understand the location of source and sink populations as well as the dynamics of those populations. Specifically, dynamic source/sink relationships (Bert et al., In preparation), in which the relative value of each local population changes rapidly (e.g., between spawning events) would be less amenable to targeted effort allocation strategies than would stable source and sink populations for which the managers can have confidence that local sink populations make little contribution to future recruitment and can therefore be more intensively harvested than can source populations which provide the vast majority of successful recruits.

Management Response Indicators

Once a management change is effected, it is necessary to be able to determine if the desired outcome of that management change was achieved. In the most direct sense, population assessments would provide the answer by comparing abundance estimates obtained prior to implementation of the new management regime with similar estimates obtained following the change. While this approach gives valuable information at the species level, it provides little if any information regarding the response of the coral reef community. To achieve the latter purpose, indicators of ecological response could be employed. Various indicators are being employed in the U.S. Caribbean to monitor and evaluate changes in coral reef ecosystem health (US EPA 2011) and at least some of these have direct application to assessment of fishery management actions. For example, the Caribbean Fishery Management Council recently reduced the allowable take of parrotfish from EEZ waters surrounding St. Croix, USVI, by an estimated 30+ percent in an effort to increase grazing rates and thereby increase the availability of critical habitat for settling propagules of threatened Acroporid corals (CFMC 2011a). Knowing that parrotfish abundance has increased in response to this action is important and can be determined via population assessment assuming the necessary data are available, but the assessment outcome provides no information regarding changes in abundance of critical *Acropora* spp. settlement substrate in response to that action. Instead, abundance of critical settlement substrate, or an index of that abundance, needs to be directly monitored as an indicator of ecosystem response to management action.

There are precedents regarding the application of ecosystem indicators as a means of monitoring the response of targeted fisheries species (Volety et al. 2009) as well as advice regarding the selection of indicators to be utilized for monitoring the success of management actions (Rice and Rochet 2005, Tulloch et al. 2011). These capabilities need to be brought to bear on questions of ecosystem response to fishery management actions, and additional capabilities need to be developed. The first author has been a long-time advocate of developing biological sensors for research and monitoring applications within the context of ocean observing systems (http://www.marine.usf.edu/flcoos/docs/arnold_meeting1.pdf). Recent publications suggest that this need is recognized worldwide (Gibbs 2012). The idea is that biological data needs to be acquired with the same temporal and spatial resolution as physical data (e.g., temperature, salinity, wind speed and direction) that presently characterizes most ocean observing assets. Integration of biological and physical data at highly resolved spatial and temporal scales would create new opportunities for populating biophysical models, mapping linkages among populations and habitats, identifying source/sink relationships and the temporal nature of those relationships, and ultimately developing fine-scale and targeted indicators of ecosystem response to management actions.

SUMMARY AND CONCLUSIONS

Commercial and recreational fisheries are integral components of the economy and culture of U.S. Caribbean communities (Stoffle et al. 2009). Fishing activities will continue into the foreseeable future, despite their potential negative impacts on Caribbean coral reef communities. This creates a challenge for the management community in the U.S. Caribbean, including both federal and state entities, to devise management approaches that maintain sustainable fisheries and healthy fishing communities while ensuring that the coral reef ecosystem upon which these fisheries (and the communities they support) depend, regain and maintain ecological viability. To achieve this goal will necessitate a broad-based and integrated approach to fisheries management.

Numerous monitoring and research studies have been completed, are underway, or are proposed for the marine waters of the U.S. Caribbean, and some of those studies have been discussed in the preceding paragraphs. Similarly, much effort is being applied to better understanding terrestrial activities that influence the marine realm although that area of research has not been addressed in this document. Efforts such as NOAA's Caribbean Strategy and NOAA in the Caribbean are moving forward with efforts to increase communication among those involved for the purpose of better integrating effort and outcomes. Fisheries management needs to become more involved in these integrative efforts, and this document outlines some of the many opportunities that exist in that regard. These are critical opportunities that cannot be missed, both because the health of the ecosystem requires it and because the taxpayers footing the bills for these efforts deserve it.

What we discuss herein is an ecosystem-based approach to fisheries management in the U.S. Caribbean. However, we consider this a bottom-up approach in contrast to the top-down approach of modeling opportunities such as Atlantis (http://atlantis.cmar.csiro.au/) which establish the requirements for input data and then challenge researchers and managers to acquire the data necessary to populate the model. Modeling remains an ideal goal, and efforts to acquire the extensive data necessary to populate such models should continue. The bottom-up approach described herein instead focuses on utilizing already available data to maximize our understanding of the potential impacts and reverberations of management decisions. This approach acknowledges the huge gaps in knowledge regarding fisheries and ecosystems in the U.S. Caribbean and appreciates the length of time and level of effort that will be required to fill those gaps. Unfortunately, Caribbean coral reefs are in peril, and action needs to be taken now. Thus, we argue that while knowledge is always an upward curve, we can't afford to wait until the asymptote is reached but instead need to act now using all of the information at hand. Certainly, as more data become available it will be important to include those data in an iterative approach. Additionally, the approach described here should provide value in determining how limited research and monitoring funds should be allocated. Integrated management efforts are being applied throughout the Caribbean basin, and both the fisheries and the coral reef communities upon which they rely will benefit from fully integrating fishery management into those efforts.

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