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REVIEWS

Monitoring programs of the U.S. Gulf of Mexico: inventory, development and use of a large monitoring database to map fish and invertebrate spatial distributions

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Abstract Since the onset of fisheries science, monitoring programs have been implemented to support stock assessments and fisheries management. Here, we take inventory of the monitoring programs of the U.S. Gulf of Mexico (GOM) surveying fish and invertebrates and conduct a gap analysis of these programs. We also compile a large monitoring database encompassing much of the monitoring data collected in the U.S. GOM using random sampling schemes and employ this database to fit statistical models to then map the spatial distributions of 61 fish and invertebrate functional groups, species and life stages of the U.S. GOM. Finally, we provide recommendations for improving current monitoring programs and designing new programs, and guidance for more comprehensive use and sharing of monitoring data, with the ultimate

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goal of enhancing the inputs provided to stock assessments and ecosystem-based fisheries management (EBFM) projects in the U.S. GOM. Our inventory revealed that 73 fisheries-independent and fisheries-dependent programs have been conducted in the U.S. GOM, most of which (85%) are still active. One distinctive feature of monitoring programs of the U.S. GOM is that they include many fisheries-independent surveys conducted almost year-round, contrasting with most other marine regions. A major sampling recommendation is the development of a coordinated strategy for collecting diet information by existing U.S. GOM monitoring programs for advancing EBFM.

Keywords Gap analysis · Inventory · Large monitoring database · Mapping · Monitoring programs · U.S. Gulf of Mexico

Introduction

In the U.S. Gulf of Mexico ("U.S. GOM"; hereafter usually simply referred to as "GOM"; Fig. 1), exploratory surveys trace back to the mid-1950's (Nichols 2004), while standardized fisheries-dependent programs and fisheries-independent surveys trace back to 1958 and 1967, respectively (SEDAR 2010; Carlson and Osborne 2013). Currently, a diversity of fisheries-dependent and fisheries-independent monitoring programs occur in the GOM, led by Federal or State agencies, universities, or other institutions [e.g., non-governmental organizations (NGOs)]. Monitoring programs are needed to support single-species stock assessments and ecosystem-based fisheries management (EBFM) efforts (Grüss et al. 2017a; O'Farrell et al. 2017). EBFM takes an integrated, holistic view of marine ecosystems, and envisions fisheries management strategies while considering trophic interactions, the influence of the abiotic environment on species dynamics and the socio-economic complexities of managing resources (Link 2002, 2010; Marasco et al. 2007; Patrick and Link 2015). Although numerous, EBFM efforts in the GOM have generally lacked implementation at the management level due to limitations such as data availability or representativeness of fish and invertebrate population trends from monitoring data (Grüss et al. 2017a; O'Farrell et al. 2017).

Fisheries-dependent monitoring programs rely on commercial or recreational fishing activities and collect data with the assistance of fishers. Catch data (e.g., biomass and species harvested) and fishing effort data (e.g., number of hooks) are commonly collected

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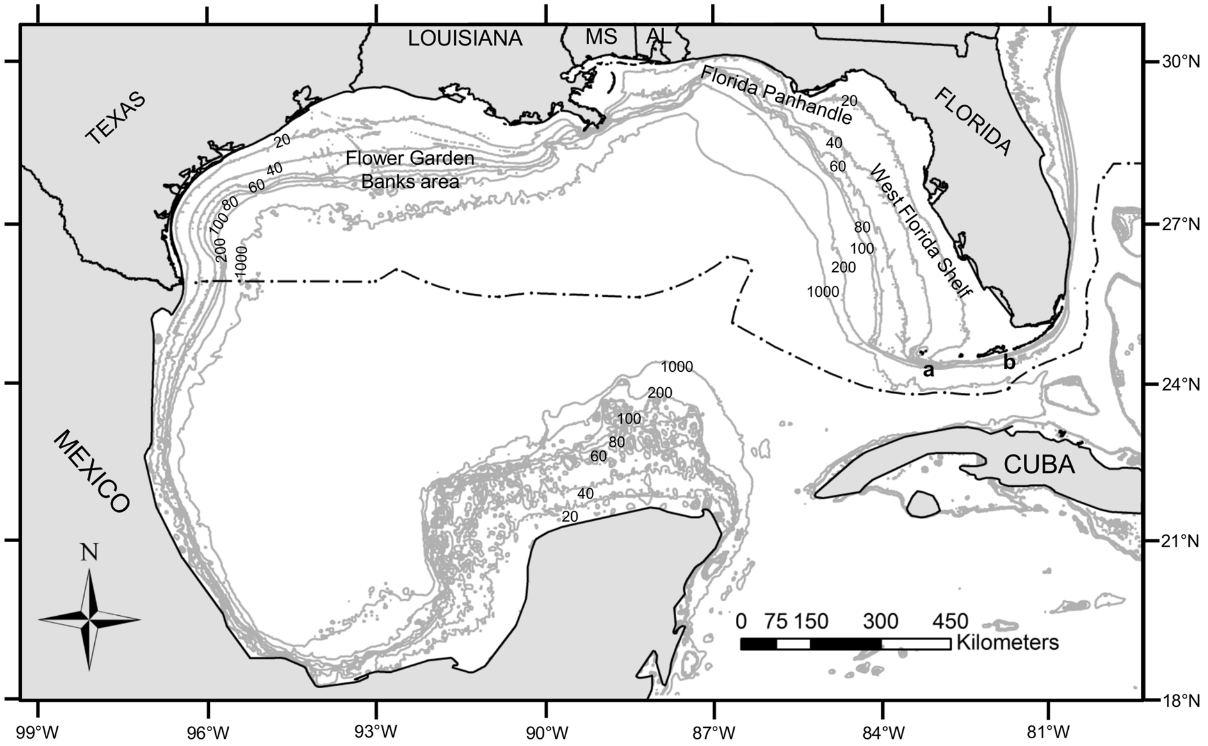

Fig. 1 Map of the Gulf of Mexico (GOM). Depth contours are labeled in 20-, 40-, 60-, 80-, 100-, 200-, and 1000-m contours. Important features are labeled and include: the Flower Garden Banks area (i.e., the large area of submerged banks of the northwestern GOM that includes the Flower Garden Banks), the West Florida Shelf, the Dry Tortugas (a), and the Florida Keys (b). *MS* Mississippi, *AL* Alabama. The black dashed-dotted line delineates the U.S. exclusive economic zone

by fisheries-dependent programs, along with biological data such as body size or maturity status. Fisher participation in such programs can be mandatory, required by law, or voluntary, and participation can be either ad hoc or randomly assigned. Data are collected via: (1) logbooks, which are a record filled out by fishers documenting fishing operations conducted for each fishing trip; (2) trip tickets, which are landings summaries often filled out by fish processors; (3) observers, who are trained personnel placed aboard fishing vessels to collect catch data and take biological samples when feasible; and (4) Access Point Angler Intercept Surveys (APAIS), where trained personnel are placed at access points (e.g., boat ramps, piers) to conduct interviews with fishers, collect catch data, and collate biological samples (Andrews et al. 2014). Logbooks and observer programs may also report the geographic coordinates of the catch and record in situ environmental data (e.g. bottom depth, bottom temperature). A key limitation of fisheries-dependent data is that they may not reflect trends in population abundance as fishers target rather than randomly sample fish and invertebrate stocks (Walters 2003; Maunder and Punt 2004; Lynch et al. 2012), and regularly update their harvest strategies based on prevailing environmental and socio-economic conditions (Marchal et al. 2006; Bourdaud et al. 2017). Yet, single-species stock assessments and the ecosystem simulation models used to assist EBFM commonly

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employ fisheries-dependent catch per unit effort (CPUE) indices of relative abundance, as fisheries-dependent data are easier and less expensive to obtain than fisheries-independent data (Maunder and Punt 2004; Lynch et al. 2012) and are generally available year-round (Bourdaud et al. 2017).

Fisheries-independent monitoring programs collect data using carefully designed scientific research surveys to enable estimates of relative abundance of targeted species. However, because going to sea is expensive and time-consuming, fisheries-independent surveys are generally conducted during specific months or seasons and, therefore, rarely provide comprehensive information about the seasonal patterns of abundance and spatial distribution of fish and invertebrates (Lynch et al. 2012; Bourdaud et al. 2017). Fisheries-independent surveys often measure in situ environmental conditions [using, e.g., CTD (Conductivity, Temperature, Depth) instruments], and sometimes collect fish stomachs, data which are critical to parameterize the diet matrix of the ecosystem modeling platforms used to assist EBFM such as Ecopath with Ecosim (EwE; e.g., Chagaris et al. 2015) and Atlantis (e.g., Tarnecki et al. 2016).

The sampling design and method employed by a given monitoring program depends on the goals and resources (Gunderson 1993; Schneider 2000; Rago 2005). Sampling designs include random, fixed and opportunistic schemes. Data collected using random sampling designs are consistent with the assumptions of most statistical methodologies by allowing all sampling units a non-zero probability of being selected (Giuffre 1997; Kitchenham and Pfleeger 2002). Fixed-station sampling methods are designed to visit the same locations repeatedly across time to follow trends in abundance. Finally, opportunistic sampling designs aim to collect data from samples that are conveniently available, such as from fishers who are willing to participate in a study. Thus, the analysis of opportunistic data generally must control for the process by which samples are obtained, e.g., using specific statistical models to account for preferential sampling in non-random surveys (Renner et al. 2015; Conn et al. 2017). Some monitoring programs combine sampling designs to decrease bias (e.g., executing APAIS, which samples opportunistically, at randomly selected access points).

Sampling methods for monitoring programs are generally determined based on the species, life stages, habitats and/or fisheries of interest. Regarding fisheries-dependent monitoring programs, logbooks, on-board observers and dockside interviews are commonly used to sample commercial fisheries, while common methods for sampling recreational fisheries include over-the-phone or mail-in questionnaires and APAIS. Regarding fisheries-independent monitoring programs, common gears for sampling include hook-and-line (e.g., vertical line, hand line, longline), seines, trawls, entangling nets (e.g., gillnet, trammel), traps, and bioacoustics (FAO 2007). Fisheries-independent programs can combine multiple sampling gears to optimize the amount of information collected (e.g., using mid-water trawls to identify species and size-classes in bioacoustics surveys).

Monitoring programs can provide encounter/non-encounter, abundance or biomass data for fish and invertebrates which can be employed to generate distribution maps. Distribution maps can assist many EBFM efforts, particularly spatially-explicit ecosystem modeling. The distribution maps provided to spatially-explicit ecosystem models are critical to define spatial patterns of predator–prey interactions (e.g., Drexler and Ainsworth 2013; Grüss et al. 2014, 2016a). Recently, a large project has been conducted in the GOM to construct annual and seasonal distribution maps for spatially-explicit ecosystem models from the predictions of geostatistical models fitted to a blending of fisheries-dependent and fisheries-independent data collected using random sampling designs (Grüss et al. 2017b, 2018c). A blending of monitoring data rather than individual monitoring datasets has been employed, because, in large marine regions exhibiting a high biodiversity like the GOM, the spatial distribution patterns of many fish and invertebrates (e.g., gag (*Mycteroperca microlepis*) and red grouper (*Epinephelus morio*)) cannot be investigated with geostatistical models when relying on only one monitoring dataset (Grüss et al. 2017b, 2018a). Monitoring data collected at fixed survey stations have not been used, because they would have required more complex statistical methods.

There is currently no inventory of the monitoring programs of the GOM surveying fish and invertebrates. Consequently, there is a lack of awareness or access to the monitoring datasets available for the

GOM, and an underutilization of these datasets for assisting single-species stock assessments and EBFM (Karnauskas et al. 2017); this is especially true regarding ecosystem modeling efforts (Grüss et al. 2016a; O'Farrell et al. 2017). There is a growing consensus among scientists and resource management organizations that improving the discoverability of data sources will greatly facilitate data sharing and collaboration, which will consequently improve the practice of ecology and lead to important insights (Whitlock 2011; Michener 2015; Cisneros-Montemayor et al. 2016). Moreover, different monitoring programs of the GOM may collect redundant information, while all failing to deliver sufficient data for certain species and life stages (Suprenand et al. 2015).

To address the above mentioned issues, we took inventory of monitoring programs of the GOM surveying fish and invertebrates and carried out a gap analysis of these programs. In the following, we first provide an overview of GOM monitoring programs. This includes summarizing the background information of each monitoring program (e.g., regions and years covered, key references), sampling characteristics and protocols, and capacity for aiding the production of distribution maps, abundance indices and diet matrices to assist single-species stock assessments and EBFM efforts in the GOM. Second, we describe the compilation of a large monitoring database for the GOM, which stores the encounter/non-encounter data collected between 2000 and 2016 by most of the monitoring programs of the GOM using random sampling schemes along with the geographic coordinates where fish and invertebrates were encountered. Third, to illustrate the usefulness of the large monitoring database for the GOM, we fit geostatistical binomial generalized linear mixed models (GLMMs) to the large monitoring database, to then produce annual and seasonal distribution maps for 61 fish and invertebrate functional groups (i.e., groups of species sharing similar ecological niches and life histories), species and life stages of the GOM. Lastly, we provide recommendations for modifications and additions to monitoring programs and develop guidance for more comprehensive use and sharing of monitoring data, with the ultimate goal of enhancing the different inputs provided to single-species stock assessments and EBFM projects in the GOM.

Overview of Gulf of Mexico monitoring programs

We identified 73 monitoring programs collecting data for fish and/or invertebrates in the GOM from reviewing SouthEast Data Assessment and Review (SEDAR) stock assessment reports and associated documents (Online Resource 1). Information was compiled for each monitoring program, including the regions and seasons covered, the sampling designs employed and key references (Online Resource 1), the sampling characteristics and protocols (Online Resource 2), and the potential contributions of each monitoring program to single-species stock assessments and EBFM efforts in the GOM (Table 1). We assigned an alias to each of the 73 monitoring programs (Table 1).

The 73 monitoring programs we identified include 49 fisheries-independent programs (67%) and 24 fisheries-dependent programs (33%). The majority of these 73 monitoring programs are conducted by Federal agencies (n = 36; 49%), 24 of them are conducted by State agencies (33%) and 13 by universities and NGOs (18%). The great majority of the monitoring programs of the GOM employ a random sampling scheme (n = 45; 62%), while the rest primarily use a fixed sampling scheme (n = 17; 23%) (Fig. 2a). The regions covered by monitoring programs of the GOM are mainly the entire U.S. GOM (n = 22; 30%) and Florida waters (n = 19; 26%) (Fig. 2b). Most monitoring programs report the geographic coordinates where fish and invertebrates were encountered (n = 58; 79%). The great majority of monitoring programs operate in spring, summer and fall, during the spring–summer semester, during the fall-winter semester, and during both the spring–summer and fall-winter semesters ($n \geq 61$; $\geq 84\%$) (Figs. 3a, b). Forty-two monitoring programs operate in winter (58%), while 41 monitoring programs cover the four seasons of the year (56%) (Fig. 3a, b). The number of monitoring programs operating in the GOM has increased linearly since 1958 and has then plateaued since 2008 (Fig. 4), and the great majority of the 73 monitoring programs we identified are still active (n = 62; 85%).

Fisheries-independent programs

Forty-nine fisheries-independent programs were identified: 16 programs conducted by Federal agencies, 20

Table 1 Overview of how Gulf of Mexico (GOM) monitoring programs operated by U.S. institutions can assist single-species stock assessments and ecosystem-based fisheries management efforts; specifically, if the collected data can be used to develop distribution maps, abundance indices, or diet matrices. An alias was assigned to each monitoring program

Program name	Distribution maps	Abundance indices	Diet matrices	Comments
National Marine Fisheries Service (NMFS)—University of Miami Dry Tortugas Visual Census Survey (Alias: DTVISUAL)				–
NMFS Panama City Video Survey (Alias: PCVIDEO)	X	X		–
NMFS Panama City Trap Survey (Alias: PCTRAP)	X	X		–
NMFS Panama City Laboratory St. Andrew Bay Juvenile Reef Fish Survey (Alias: PCJUV)		X		–
NMFS Gulf of Mexico Shark Pupping and Nursery Survey (Alias: GULFSPAN)	X	X		–
NMFS Red Snapper/Shark Bottom Longline Survey (Alias: BLL)	X	X	X	Collects diet data, but not on a regular basis
NMFS Cuba/Mexico Collaborative Bottom Longline Survey (Alias: MXCBBLL)	X	X		–
NMFS Congressional Supplemental Sampling Program (CSSP)—Vertical Line Survey (Alias: CSSPVL)	X	X		–
NMFS CSSP—Longline Survey (Alias: CSSPLL)	X	X		–
NMFS Pelagic Acoustic Trawl Survey (Alias: PELACTR)	X	X	X	–
Southeast Monitoring and Assessment Program (SEAMAP) Ichthyoplankton Survey (Alias: ICHTHYOP)	X	X		–
SEAMAP Reef Fish Video Survey (Alias: VIDEO)	X	X		–
Northern Gulf of Mexico Continental Slope Habitats and Benthic Ecology Study Survey (Alias: DGOMB)	X			–
SEAMAP Groundfish Trawl Survey (Alias: TRAWL)	X	X	X	Collects diet data on a regular basis, but only in the eastern GOM
SEAMAP Gulf of Mexico Inshore Bottom Longline Survey (Alias: INBLL)	X	X	X	Collects diet data, but not on a regular basis
SEAMAP Gulf of Mexico Vertical Longline Survey (Alias: VL)	X	X	X	Collects diet data, but not on a regular basis
NMFS Reef Fish logbook program—commercial handline (Alias: COMHL)		X		–
NMFS Reef Fish logbook program—commercial longline (Alias: COMLL)		X		–
NMFS Reef Fish logbook program—commercial trap (Alias: COMTRAP)		X		–
NMFS Trip Interview Program (Alias: TIP)		X		–
NMFS Pelagic Observer Program (Alias: POP)	X	X	X	–
NMFS Shark Bottom Longline Observer Program (Alias: SBLOP)	X	X	X	–
NMFS Southeast Gillnet Observer Program (Alias: OBSGILL)	X	X		–
Southeastern Shrimp Fisheries Observer Coverage Program (Alias: OBSSHRIMP)	X	X	X	–
NMFS Menhaden Purse Seine Fisheries Observer Coverage (Alias: OBSMEN)				Confidential data; limited to a single season and year

Table 1 continued

Program name	Distribution maps	Abundance indices	Diet matrices	Comments
Reef fish bottom longline observer program (Alias: OBSLL)	X	X	X	–
Reef fish vertical line observer program (Alias: OBSVL)	X	X	X	–
NMFS Menhaden Sampling Program (Alias: SAMMEN)			X	–
Marine Recreational Fisheries Statistics Survey (Alias: MRFSS)		X		–
Marine Recreational Information Program (Alias: MRIP)		X		–
Recreational Billfish Survey (Alias: RBS)				–
NMFS Southeast Region Headboat Survey (Alias: SRHS)		X		–
Everglades National Park Creel Survey (Alias: ENPCREEL)		X		–
Gulf of Mexico Fisheries Information Network (GulfFIN) Trip Ticket Program (Alias: GULFFINTRIP)				–
GulfFIN Headboat Observer Program (Alias: GULFFINOBS)		X		–
GulfFIN Biological Sampling (Alias: GULFFINSAM)		X		–
Fish and Wildlife Research Institute (FWRI) Trawl Survey (Alias: FLTRAWL)	X	X	X	Collects diet data on a regular basis
FWRI Baitfish Trawl Survey (Alias: FLBAIT)	X	X	X	Collects diet data on a regular basis
FWRI Bay Seine Survey (Alias: FLBAY)	X	X	X	Collects diet data on a regular basis
FWRI Haul Seine Survey (Alias: FLHAUL)	X	X	X	Collects diet data on a regular basis
FWRI Purse Seine Survey (Alias: FLPURSE)	X	X	X	Collected diet data on a regular basis when it was in effect
FWRI Trammel Survey (Alias: FLTRAM)	X	X		–
FWRI Reef Fish Trap Survey (Alias: FLTRAP)	X	X		–
FWRI Reef Fish Video Survey (Alias: FLVIDEO)	X	X		–
Alabama Marine Resources Division (AMRD) Fisheries Assessment and Monitoring Program (FAMP) Trawl Survey (Alias: ALTRAWL)		X	X	–
AMRD FAMP Beam Plankton Trawl Survey (Alias: ALPLK)		X		–
AMRD FAMP Seine Survey (Alias: ALSEINE)		X	X	–
AMRD FAMP Gillnet Survey (Alias: ALGILL)	X	X		–
Louisiana Department of Wildlife and Fisheries (LDWF) Shrimp Trawl Survey (Alias: LASHRIMP)		X	X	–
LDWF Trawl Survey (Alias: LATRAWL)		X	X	–
LDWF Seine Survey (Alias: LASEINE)		X	X	–
LDWF Trammel Survey (Alias: LATRAM)		X		–
LDWF Gillnet Survey (Alias: LAGILL)		X		–
Texas Parks and Wildlife (TPWD) Trawl Survey (Alias: TXTRAWL)	X	X	X	–
TPWD Seine Survey (Alias: TXSEINE)	X	X	X	–
TPWD Gillnet Survey (Alias: TXGILL)	X	X		–
FWRI Gulf Reef Fish Survey (Alias: FLRECREEF)		X		–

Table 1 continued

Program name	Distribution maps	Abundance indices	Diet matrices	Comments
FWRI For-Hire At-Sea Observer Program (Alias: FLOBS)	X	X		–
Louisiana Recreational Creel Survey (Alias: LACREEL)		X		–
TPWD Texas Marine Sport-Harvest Monitoring Program Survey (Alias: TXFD)		X		–
Continental Shelf Characterization, Assessment, and Mapping Project (Alias: CSCAMP)	X			–
Center for Integrated Modeling and Analysis of Gulf Ecosystems Bottom Longline Survey (Alias: CIMAGE)	X		X	–
Deep Pelagic Nekton Dynamics of the Gulf of Mexico Survey (Alias: DEEPEND)	X		X	Collected diet data on a regular basis when it was in effect
Florida State University Estuarine Gag Survey (Alias: FSUEST)				–
University of Florida Reef Survey (Alias: UFREEF)				–
Dauphin Island Sea Lab Bottom Longline Survey (Alias: DISLBLL)	X	X	X	Collects diet data, but not on a regular basis
Gulf Coast Research Laboratory (GCRL) Trawl Survey (Alias: MSTRAWL)	X	X	X	Collected diet data, but not on a regular basis
GCRL Seine Survey (Alias: MSSEINE)		X	X	Collected diet data, but not on a regular basis
GCRL Beam Plankton Net Survey (Alias: MSPLK)		X		Collected diet data, but not on a regular basis
GCRL Sport Fish Shark Gillnet Survey (Alias: MSGILL)	X	X		–
GCRL Sport Fish Shark Handline Survey (Alias: MSHAND)	X	X	X	–
Reef Environmental Education Foundation (REEF) Fish Survey Project (Alias: REEF)	X	X		–
Mote Marine Laboratory Gill Net Survey (Alias: MMLGILL)	X	X		–

programs from State agencies, and 13 programs conducted by other institutions (universities and NGOs). These monitoring programs differ in sampling protocol, region covered and seasonality. The bulk of fisheries-independent programs employs a random sampling scheme (n = 31; 63%), while the rest primarily adopt a fixed sampling scheme (n = 14; 29%) (Fig. 2c). The most common sampling methods used by fisheries-independent programs of the GOM are trawls (n = 13; 27%), seine (n = 7; 14%), longline (n = 7; 14%) and gillnet (n = 6; 13%) (Fig. 2d). The regions most sampled by these programs are Florida waters (n = 16; 33%), the entire U.S. GOM (n = 7; 15%) and Louisiana waters (n = 6; 12%) (Fig. 2e). Most fisheries-independent programs operate in spring, summer and fall, during the spring–summer semester, during the fall-winter semester, and during both the spring–summer and fall-winter semesters ($n \geq 38$; $\geq 78\%$) (Figs. 3c, d); 43% of them (n = 21) operate in winter, while 41% of them (n = 20) cover the four seasons of the year (56%) (Figs. 3c, d).

Fisheries-dependent programs

Twenty fisheries-dependent programs from Federal agencies and four fisheries-dependent programs conducted by U.S. State agencies were identified, which sample commercial fisheries, recreational fisheries, or a combination of the two. The sampling designs most employed by fisheries-dependent programs of the GOM are random (n = 14; 58%) and opportunistic sampling schemes (n = 5; 21%) (Fig. 2f). The sampling methods used by these programs include observers (n = 9; 37%), port agents (n = 5; 21%),

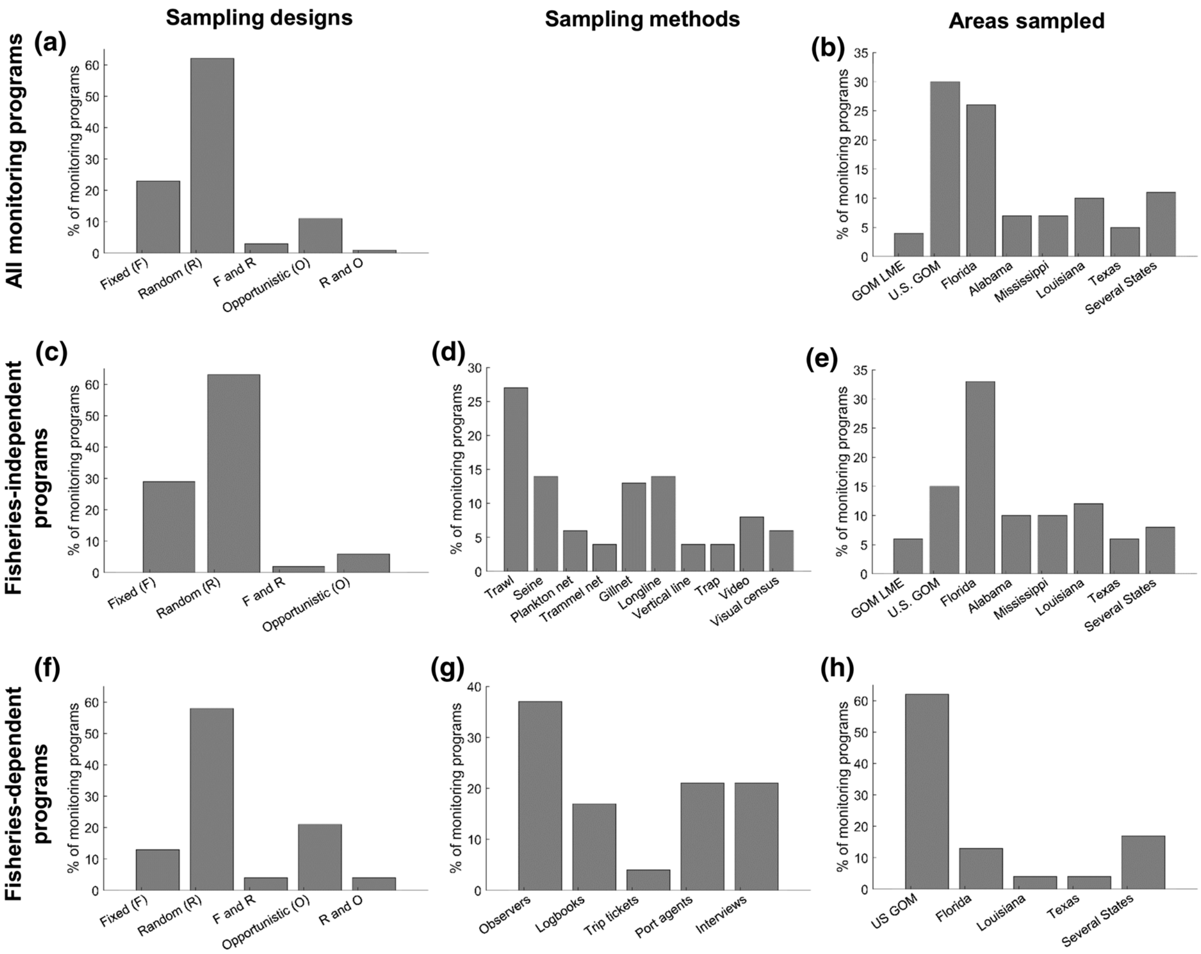

Fig. 2 Sampling designs and methods used and regions sampled by all monitoring programs (**a**, **b**), fisheries-independent programs (**c**–**e**) and fisheries-dependent programs (**f**–**h**) of the U.S. Gulf of Mexico. *U.S. GOM* U.S. Gulf of Mexico, *GOM LME* Gulf of Mexico Large Marine Ecosystem

interviews (n = 5; 21%), logbooks (n = 4; 17%), and trip tickets (n = 1; 4%) (Fig. 2g). Fisheries-dependent programs of the GOM cover mainly the entire U.S. GOM (n = 15; 62%), several U.S. GOM States (n = 4; 17%) and Florida waters (n = 3; 13%) (Fig. 2h). Almost all of these programs operate during all seasons of the year; in particular, 88% of them (n = 21) operate in winter (Figs. 3e, f).

Potential contributions of monitoring programs of the Gulf of Mexico to single-species stock assessments and EBFM efforts

A total of 42 monitoring programs in the GOM collect data using random sampling schemes and record the geographic coordinates where fish and invertebrates are encountered, whose encounter/non-encounter data can be combined to generate distribution maps, as was recently done in Grüss et al. (2017b, 2018c) (Table 1). Both random and fixed location data can be used for tracking trends in fish and invertebrate abundance over time. Among the monitoring programs of the GOM that are still active, five collate diet data on a regular basis, and two others on an occasional basis. However, diet data could potentially be collected by twenty-six still-active monitoring programs of the GOM that either use trawls, seines, longlines or vertical lines or put observers onboard fishing vessels using these gears (Table 1).

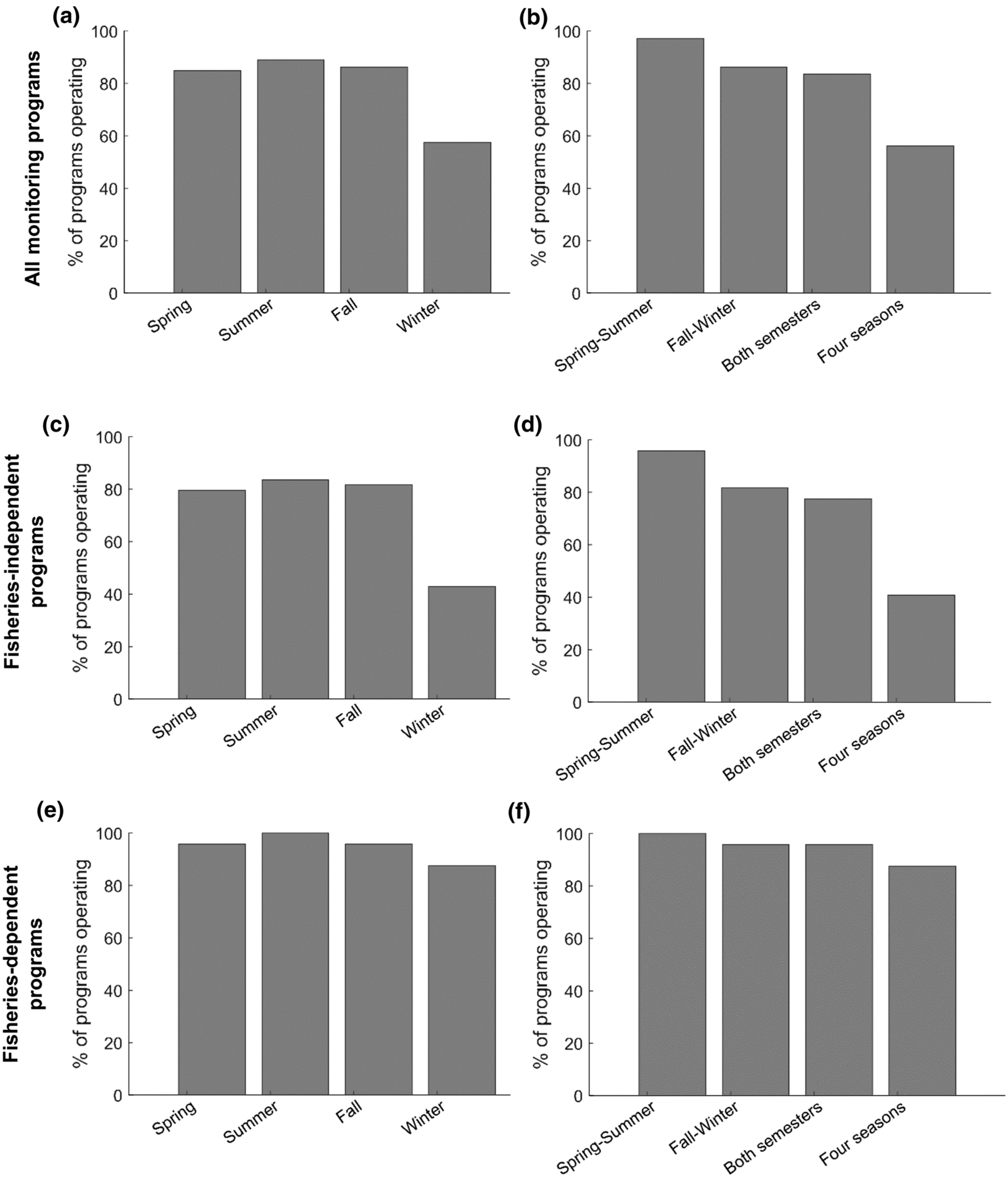

Fig. 3 Seasons covered by all monitoring programs (**a**, **b**), fisheries-independent programs (**c**, **d**) and fisheries-dependent programs (**e**, **f**) of the U.S. Gulf of Mexico. Spring = April–June; Summer = July–September; Fall = October–December; Winter = January–March; Spring–Summer = April–September; Fall–Winter = October–March

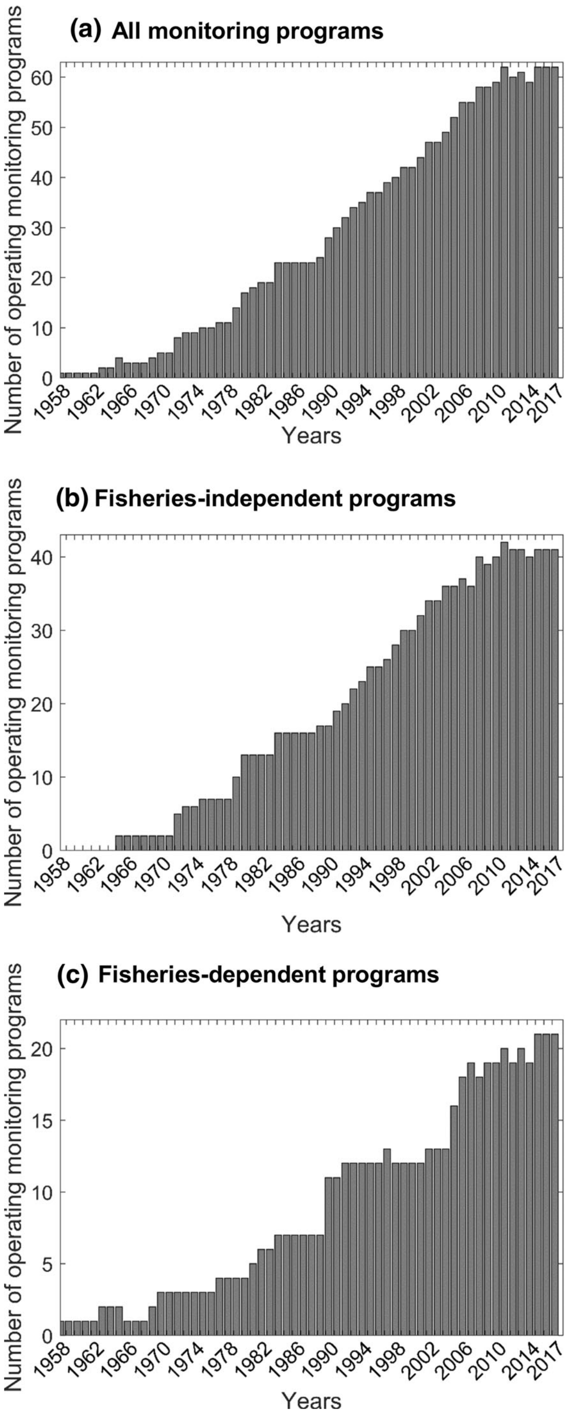

Fig. 4 Evolution of the number of monitoring programs (**a**), fisheries-independent programs (**b**) and fisheries-dependent programs (**c**) operating in the U.S. Gulf of Mexico over the period 1958–2017

Compilation of a large monitoring database for the Gulf of Mexico

We contacted the Federal and State agencies, universities and NGOs which conduct monitoring programs in the GOM using random sampling schemes and report geographic coordinates. We requested data collected during the period of 2000–2016 for integration into a large monitoring database for the GOM (Table 2). We received 34 of the monitoring datasets described in Online Resources 1 and 2, including 27 fisheries-independent datasets and seven fisheries-dependent datasets.

Application of the large monitoring database for the Gulf of Mexico

To illustrate the usefulness of the large monitoring database for the GOM, we employ it here to construct annual and seasonal distribution maps for 61 fish and invertebrate functional groups, species and life stages (Table 3 and Online Resource 3). These 61 functional groups, species, and life stages reflect key fisheries stocks and/or their prey and are represented in at least one of two major ecosystem models of the GOM: “Atlantis-GOM”, which is an Atlantis model for the entire GOM Large Marine Ecosystem (Ainsworth et al. 2015); and “WFS Reef fish EwE”, which is an EwE model for the West Florida Shelf (Chagaris 2013; Chagaris et al. 2015). Atlantis-GOM and WFS Reef fish EwE were both designed to represent a comprehensive suite of the functional groups, species and life stages of the GOM. The methodology that we used for generating distribution maps and that we describe in detail below was developed in Grüss et al. (2017b, 2018c) for providing distribution maps to the OSMOSE ecosystem model of the West Florida Shelf (“OSMOSE-WFS”; Grüss et al. 2015, 2016b, c).

For each of the functional groups/species/life stages listed in Table 3, we extracted the following information from each of the 34 fisheries-independent and fisheries-dependent monitoring datasets included in the large monitoring database for the GOM: (1) the longitudes and latitudes at which the sampling events occurred; (2) the years and months during which the sampling events occurred; and (3) whether each functional group/species/life stage was encountered or not during the sampling events (0’s and 1’s). Body length estimates recorded by monitoring programs and

Table 2 Monitoring programs comprising the large monitoring database for the Gulf of Mexico (GOM)

Program alias	Quality (for the purpose of this study)	Why considered to be of high/low quality (for the purpose of this study)?
PCVIDEO	High	Collected data at multiple sites
PCTRAP	High	Collected data at multiple sites
GULFSPAN	High	Collected data at multiple sites in northwestern Florida
BLL	High	Collected data at multiple sites over the entire GOM
CSSPVL	High	Collected data collected at multiple sites over the entire GOM
CSSPLL	High	Collected data at multiple sites over the entire GOM
PELACTR	High	Collected data at multiple sites over the entire GOM
VIDEO	High	Collected data at multiple sites over the entire GOM
DGOMB	Low	Collected data at a limited number of sites during summer months between 2000 and 2002 in the offshore areas of the GOM only
TRAWL	High	Collected data at multiple sites over the entire GOM
INBLL	High	Collected data at multiple sites over a large fraction of the GOM
VL	High	Collected data at multiple sites over a large fraction of the GOM
POP	High	Collected data at multiple sites over the entire GOM and in international waters
SBLOP	High	Collected data at multiple sites over the entire GOM
OBSGILL	Low	Collected data at multiple sites in the eastern GOM; but some data were collected in very close proximity (using different panels of the same gear)
OBSSHRIMP	High	Collected data at multiple sites over the entire GOM
OBSLL	High	Collected data at multiple sites over the entire GOM
OBSVL	High	Collected data at multiple sites over the entire GOM
FLTRAWL	High	Collected data at multiple sites
FLBAY	High	Collected data at multiple sites
FLHAUL	High	Collected data at multiple sites
FLPURSE	High	Collected data at multiple sites
FLTRAP	High	Collected data at multiple sites
FLVIDEO	High	Collected data at multiple sites
ALGILL	High	Collected data at multiple sites over multiple years and months
TXTRAWL	High	Collected data at multiple sites over the entire Texas coastal zone
TXSEINE	High	Collected data at multiple sites over the entire Texas coastal zone
TXGILL	High	Collected data at multiple sites over the entire Texas coastal zone
FLOBS	High	Collected data at multiple sites off West Florida
DEEPEND	Low	Available data were collected at a limited number of sites during May and August for two consecutive years in the offshore areas of central GOM only
MSTRAWL	High	Collected data at multiple sites
MSGILL	Low	Collected data at multiple sites; but teleosts were documented by number caught in each panel in later years only
MSHAND	High	Collected data at multiple sites
REEF	High	Collected data at multiple sites over the entire GOM

body length benchmarks (e.g., body length at age 1) from FishBase (Froese and Pauly 2015) and SeaLifeBase (Palomares and Pauly 2015) were employed to separate life stages. As was done in Grüss et al. (2018c), we gauged the quality of the 34 datasets for the purpose of this study (e.g., does the monitoring program have a high or a low spatio-temporal resolution?) as we extracted information from them

Table 3 Functional groups, species, and life stages considered in the present study

Functional group	Representative species	Life stages considered for this functional group
Benthic feeding sharks	Bonnethead (*Sphyrna tiburo*)	Juvenile and adult life stages
Large sharks	Sandbar shark (*Carcharhinus plumbeus*)	Juvenile and adult life stages
Blacktip shark	Blacktip shark (*Carcharhinus limbatus*)	Juvenile and adult life stages
Small sharks	Atlantic sharpnose shark (*Rhizoprionodon terraenovae*)	All life stages combined
Skates and rays	Cownose ray (*Rhinoptera bonasus*)	All life stages combined
Cobia	Cobia (*Rachycentron canadum*)	All life stages combined
King mackerel	King mackerel (*Scomberomorus cavalla*)	All life stages combined
Spanish mackerel	Spanish mackerel (*Scomberomorus maculatus*)	Juvenile and adult life stages
Jacks, wahoo, dolphinfish and tunnies	Dolphinfish (*Coryphaena hippurus*)	All life stages combined
Red snapper	Red snapper (*Lutjanus campechanus*)	Younger juveniles (ages 0–1), older juveniles (ages 1–2) and adults (ages 2 +)
Vermilion snapper	Vermilion snapper (*Rhomboplites aurorubens*)	All life stages combined
Other snappers	Gray (mangrove) snapper (*Lutjanus griseus*)	All life stages combined
Tilefish	Golden tilefish (*Lopholatilus chamaeleonticep*	All life stages combined
Yellowedge grouper	Yellowedge grouper (*Hyporthodus flavolimbatus*)	All life stages combined
Other deep water groupers	Snowy grouper (*Hyporthodus niveatus*)	All life stages combined
Gag grouper	Gag grouper (*Mycteroperca microlepis*)	Younger juveniles (ages 0–1), older juveniles (ages 1–3) and adults (ages 3 +)
Red grouper	Red grouper (*Epinephelus morio*)	Younger juveniles (ages 0–1), older juveniles (ages 1–3) and adults (ages 3 +)
Black grouper	Black grouper (*Mycteroperca bonaci*)	All life stages combined
Other shallow water groupers	Scamp (*Mycteroperca phenax*)	All life stages combined
Goliath grouper	Goliath grouper (*Epinephelus itajara*)	All life stages combined
Triggerfish and hogfish	Gray triggerfish (*Balistes capriscus*)	All life stages combined
Amberjacks	Greater amberjack (*Seriola dumerili*),	All life stages combined
Sea basses	Black sea bass (*Centropristis striata*)	All life stages combined
Reef carnivores	White grunt (*Haemulon plumieri*)	All life stages combined
Reef omnivores	Doctorfish (*Acanthurus chirurgus*)	All life stages combined
Seatrouts	Spotted seatrout (*Cynoscion nebulosus*)	Juvenile and adult life stages
Flatfish	Gulf flounder (*Paralichthys albigutta*)	All life stages combined
Sciaenidae	Gulf kingfish (*Menticirrhus littoralis*)	Juvenile and adult life stages
Pinfish	Pinfish (*Lagodon rhomboides*)	Juvenile and adult life stages
Menhadens	Gulf menhaden (*Brevoortia patronus*)	Juvenile and adult life stages
Small pelagic fish	Scaled sardine (*Harengula jaguana*)	All life stages combined
Mullets	Striped mullet (*Mugil cephalus*)	All life stages combined
Squids	Atlantic brief squid (*Lolliguncula brevis*)	All life stages combined
Pink shrimp	Pink shrimp (*Farfantepenaeus duorarum*)	Juvenile and adult life stages

Table 3 continued

Functional group	Representative species	Life stages considered for this functional group
Brown shrimp	Brown shrimp (*Farfantepenaeus aztecus*)	Juvenile and adult life stages
White shrimp	White shrimp (*Litopenaeus setiferus*)	Juvenile and adult life stages
Large crabs	Blue crab (*Callinectes sapidus*)	All life stages combined
Octopods	Common octopus (*Octopus vulgaris*)	All life stages combined
Stomatopods	Mantis shrimp (*Squilla empusa*)	All life stages combined
Lionfish	Red lionfish (*Pterois volitans*)	All life stages combined
Echinoderms and gastropods	Sand dollar (*Mellita quinquiesperforata*)	All life stages combined
Bivalves	Calico scallop (*Argopecten gibbus*)	All life stages combined
Sessile epibenthos	Balane (*Balanus trigonus*)	All life stages combined
Jellyfish	Common jellyfish (*Aurelia aurita*)	All life stages combined

A representative species was identified for each of the functional groups. The full list of species making up each of the functional groups is provided in Online Resource 3

(Table 2); this allowed us to use only the datasets with high quality (for the purpose of this study) when fitting geostatistical binomial GLMMs in data-rich situations (i.e., in situations where numerous datasets can be employed for statistical modeling). Finally, we conducted a literature review to determine whether or not we should generate distribution maps for different seasons for the functional groups, species and life stages listed in Table 3 (e.g., because the functional group/species/life stage under consideration undertakes seasonal migrations: Online Resource 5).

After extraction of the necessary information from the 34 datasets for all the functional groups, species and life stages, we determined which of the monitoring programs included in the large monitoring database for the GOM would be employed to fit geostatistical binomial GLMMs. To select datasets from the large monitoring database for the GOM for a given functional group/species/life stage/season, we applied the following rules: (1) datasets with fewer than 50 encounters were excluded, following the recommendations of Leathwick et al. (2006) and Austin (2007); (2) years with fewer than five encounters were excluded; and (3) a dataset scored to have low quality for the purpose of this study should be excluded in data-rich situations. The two latter rules were established in Grüss et al. (2017b, 2018c), as well as in Grüss et al. (2018a) where generalized additive models were fitted to a blending of monitoring data for producing preference functions for the WFS Reef fish Ecospace model.

Statistical modeling

We applied the statistical modeling approach of Grüss et al. (2017b, 2018c). This approach relies on geostatistical binomial GLMMs which predict encounter probabilities, with Gaussian Markov random fields used to model spatial residuals in encounter probability. Geostatistical GLMMs are built on the principle that probability of encounter at a given site is more similar to probability of encounter at neighboring sites than probability encounter at distant locations, i.e., these GLMMs model spatial structure at a fine spatial scale. Thus, geostatistical binomial GLMMs estimate a smoothed surface that depicts how probability of encounter varies spatially (Thorson et al. 2015; Grüss et al. 2017b). Our geostatistical binomial GLMMs are implemented using the R package *VAST*, which is publicly available online (Thorson et al. 2015).

The Gaussian Markov random fields employed to model spatial residuals in probability of encounter were approximated using 1000 “knots” (Thorson et al. 2015; Grüss et al. 2017b). For each functional group/species/life stage/season, we determined the geographic position of knots by applying a *k*-means algorithm to the geographic positions of the data extracted from the large monitoring database. The *k*-means algorithm defines the locations of knots spatially after having taken into account the sampling intensity of the monitoring programs retained for the functional group/life stage/species/season under consideration (Thorson et al. 2015).

Geostatistical binomial GLMMs were fitted to the encounter/non-encounter data extracted from the large monitoring database following the equation:

$$p_i = logit^{-1}\left(\sum_{t=1}^{n_t} \beta_t Y_{i,t} + \sum_{m=1}^{n_m} \gamma_m G_{i,m} + \varepsilon_{J(i)}\right) \qquad (1)$$

where p_i is the probability of encounter at site $s(i)$; $\varepsilon_{J(i)}$ are the random effects of the spatial residuals in probability of encounter on the logit scale at $J(i)$, the knot that is nearest to sample i; $\sum_{m=1}^{n_m} \gamma_m G_{i,m}$ is the monitoring program effect on p_i on the logit scale; and $\sum_{t=1}^{n_t} \beta_t Y_{i,t}$ is the fixed year effect on p_i on the logit scale. We implemented restricted maximum-likelihood (REML), which allowed us to treat the monitoring program factor as a random effect with a "flat" prior and, therefore, not to have to set the monitoring program factor to a given level when making predictions with the fitted GLMMs (Harville 1974).

Regarding monitoring program effect, the design matrix $G_{i,m}$ is such that $G_{i,m}$ is 1 for the program m which obtained sample i and 0 otherwise; γ_m is a monitoring program effect, such $\gamma_m = 0$ for the program m associated with the largest sample size for the functional group/species/life stage/season under consideration to allow for the identifiability of all year effects β_t; and n_m is the total number of programs retained for the functional group/species/life stage/season under consideration.

Regarding the fixed year effect, the design matrix $Y_{i,t}$ is such that $Y_{i,t}$ is 1 for the year t during which sample i was obtained and 0 otherwise; β_t is an intercept that varies among years; and n_t is the total number of years for which monitoring data are available for the functional group/species/life stage/season under consideration. To predict probability of encounter in any site i, the geostatistical GLMMs employ data in every year t. Then, the intercept term β_t serves to scale probability of encounter up or down amongst years, where the change in probability of encounter (in the logit scale) between years is the same for any location. Thus, β_t takes into account the fact that different years may have a lower or higher probability of encounter for all locations in a given year. Then, if the spatial extent of a given program is altered amongst years, the geostatistical GLMMs takes this into account by comparing it with the predicted probability of encounter at each location. It is important to note that we are assuming here that overall abundance changes will only scale local densities but not change spatial distributions, which may not be the case for many fish species (e.g., Frisk et al. 2011).

The spatial residuals in probability of encounter are random effects following a multivariate normal distribution:

$$\boldsymbol{\varepsilon} \sim MN(0, \boldsymbol{\Sigma}) \qquad (2)$$

where MN is the multivariate normal distribution, with expected value fixed to 0 for each location; and $\boldsymbol{\Sigma}$ is a covariance matrix for $\boldsymbol{\varepsilon}$ at each location, assumed to be stationary and to follow a Matérn distribution with smoothness $v = 1$ accounting for geometric anisotropy (i.e., the potential for spatial structure to vary with both distance and direction) (Thorson et al. 2015, 2016).

The parameters of the geostatistical GLMMs were estimated using Template Model Builder (Kristensen et al. 2016) called within the R statistical environment (R Core Development Team 2013). After the GLMMs were fitted, they were evaluated using a standard test of convergence and Pearson residuals (Thorson et al. 2015; Grüss et al. 2017b, 2018c). The test of convergence consisted of determining whether any of the following parameters hit an upper or lower bound, and whether the absolute value of the final gradient for each of these parameters was close to zero: the linear transformation representing geometric anisotropy in our Matérn functions (H), the range parameter of the Matérn functions (determining the distance over which covariance reaches 10% of its pointwise value), and the standard deviation of $\boldsymbol{\varepsilon}$ (σ_{ε}). Pearson residuals were used to gauge the fits of the geostatistical GLMMs; their calculations are described in detail in Online Resource 4.

Production of distribution maps for the GOM

We used the fitted geostatistical binomial GLMMs to generate probability of encounter maps for the GOM for each functional group/species/life stage/season. To be able to generate probability of encounter maps, we constructed 0.18° (20 km × 20 km) prediction grids for each of the functional groups/species/life stages/

seasons from a spatial grid covering the entire U.S. GOM. The prediction grids were produced based on the ranges of longitude, latitude and depth at which the functional groups/species/life stages were encountered by monitoring programs year-round or at different seasons. Depth was estimated using the SRTM30 PLUS global bathymetry grid obtained from the Gulf of Mexico Coastal Ocean Observing System (GCOOS 2016). The monitoring data used to fit GLMMs for all the functional groups/species/life stages/seasons cover the entire GOM, with the exception of younger juvenile gag. Only three monitoring programs implemented in Florida (FLBAY, FLHAUL, and FLTRAWL; Online Resource 5) provided sufficient encounter data for younger juvenile gag, all of which cover critical habitat for the life stage (Ingram et al. 2013).

For distribution map generation, we assumed, for each functional group/species/life stage/season, that the Gaussian Markov random field in each cell of their prediction grid is equal to the value of the Gaussian Markov random field at the nearest knot. Firstly, for each functional group/species/life stage/season, we employed the fitted GLMM for that functional group/species/life stage/season to produce a probability of encounter map for each of the sampling years. Secondly, the probability of encounter maps for each sampling year were averaged to generate one average probability of encounter map for each functional group/species/life stage/season (Grüss et al. 2017b, 2018c).

Results of the application of the large monitoring database

The monitoring programs and sampling years retained for the application of the large monitoring database varied greatly from one functional group/species/life stage/season to another (Online Resource 5). The criteria established above were followed for all the functional groups, species, life stages and seasons, except: (1) younger juvenile red grouper; and (2) octopods. In the case of younger juvenile red grouper, encounters were so scarce that two monitoring programs with fewer than 50 encounters (FLHAUL and TRAWL) were retained. In the case of octopods, we retained one monitoring program with only 38 encounters (OBSSHRIMP), so as to have a large enough set of encounter/non-encounter data for statistical modeling.

With respect to statistical modeling, all models converged for the functional groups, species, life stages and seasons considered (Online Resource 5). Moreover, for all the functional groups/species/life stages/seasons, observed encounter frequencies for either low or high probability samples were generally within or extremely close to the 95% confidence interval for predicted probability of encounter (Online Resource 5). Exceptions to this general pattern occurred for: (1) the “jacks, dolphinfish, wahoos and tunnies” group; (2) older juvenile red snapper (*Lutjanus campechanus*); (3) vermilion snapper (*Rhomboplites aurorubens*); (4) the “triggerfish and hogfish” group; (5) sea basses; (6) juvenile menhadens in fall-winter; and (7) stomatopods. For these functional groups/species/life stages/seasons, observed encounter frequency for the highest probability samples were noticeably smaller than the 95% confidence interval for predicted probability of encounter. However, geostatistical binomial GLMMs did not systematically over- or underestimate probability of encounter in any area of the GOM for these functional groups/species/life stages/seasons (Online Resource 5).

A total of 49 annual maps and 24 seasonal maps (for 12 different functional groups/species/life stages) were produced (Online Resource 6). The distribution maps for different life stages of a given species generally reflect ontogenetic habitat shifts, e.g., migrations offshore and into deeper waters with age. Thus, for example, younger juvenile red snapper is primarily encountered on the shelves of Texas, Louisiana, Mississippi and Alabama, in the Florida Panhandle region, and near the Dry Tortugas and the Florida Keys, at depths ranging between 20 and 60 m. Older juvenile red snapper has a high probability to be encountered all over the GOM shelf at depths ranging between 40 and ~ 200 m. Finally, adult red snapper is mainly encountered on the shelf regions of Texas, Louisiana, Mississippi and Alabama where depth varies between 80 and 200 m. Another example is that of brown shrimp (*Farfantepenaeus aztecus*), whose juveniles are generally encountered in the shallow (0–20 m) areas of the western GOM, while adult brown shrimp hotspots are essentially found in the areas of the western GOM where depth ranges between 20 and ~ 100 m.

The distribution maps we produced also show that functional groups and species of a given family or complex can be found in different regions of the GOM (Online Resource 6). For example, gag and red grouper tend to be encountered all over the West Florida Shelf, while black grouper (*Mycteroperca bonaci*) and goliath grouper (*Epinephelus itajara*) are almost exclusively encountered in the southernmost region of the West Florida Shelf. The other species of shallow-water grouper complex (the "other shallow water groupers group"), such as scamp (*Mycteropera phenax*), have a high probability to be encountered all over the edge of the West Florida Shelf, as well as on the edge of the Alabama shelf and in the Flower Garden Banks area. A second example of species-specific spatial distribution patterns is that of the Peneidae family; while pink shrimp (*Farfantepenaeus duorarum*) is mainly encountered in the eastern GOM, brown shrimp and white shrimp (*Litopenaeus setiferus*) hotspots are almost exclusively found in the western GOM.

Discussion of the application

The application of the statistical methodology developed in Grüss et al. (2017b, 2018c) to a large database including 34 monitoring datasets of the GOM allowed us to construct 49 annual maps and 24 seasonal maps (for 12 different functional groups/species/life stages). This endeavor illustrated the usefulness of the large monitoring database for the GOM in providing substantial data for a diversity of fish and invertebrate functional groups, species and life stages, including younger juvenile fish (e.g., younger juvenile gag) for which it was previously impossible to produce distribution maps or robust abundance indices (e.g., Ingram et al. 2013). Using Pearson residuals, the predictions made by all the GLMMs developed in the present study were demonstrated to be reasonable (Online Resource 5). Moreover, the spatial distribution patterns predicted by our GLMMs concur with the literature (Table 4). Therefore, the 73 distribution maps we generated represent considerable advancements in understanding the spatial distributions of fish and invertebrates of the GOM. We recommend their use to assist EBFM efforts in the GOM, including, among others, simulations with ecosystem models (Ainsworth et al. 2015; Grüss et al. 2016b, c, 2018b), ecosystem status reports (Karnauskas et al. 2013a, 2017), evaluation of the potential efficacy of marine protected areas (Le Pape et al. 2014; Brock 2015; Grüss et al. 2017a), evaluation of the degree of spatial overlap between fish species and large-scale disturbances (e.g., red tide (*Karenia brevis*), a type of harmful algal bloom; SEDAR 2009a, 2009b; Sagarese et al. 2015), and identification of bycatch hotspots in the reef fish and shrimp fisheries for then developing bycatch mitigation strategies (Scott-Denton et al. 2012; Monk et al. 2015). Our 73 distribution maps will also make a useful addition to the Gulf of Mexico Data Atlas, a website providing biological, environmental and socio-economic information for the U.S. GOM (NCEI 2017).

The 61 functional groups, species and life stages considered in this study were selected because they are represented in at least one of two major ecosystem models of the GOM (Atlantis-GOM and WFS Reef fish EwE). Future studies could extract data from the large monitoring database for the GOM compiled in this study (or an enhanced version of it) to produce distribution maps and abundance indices for other species and life stages (e.g., juveniles and adults of gray triggerfish (*Balistes capriscus*), a species which was included in the "triggerfish and hogfish" functional group in the present study). This will be especially useful for those species that are assessed individually within the SEDAR process in the GOM, including yellowtail snapper (*Ocyurus chrysurus*), hogfish (*Lachnolaimus maximus*), greater amberjack (*Seriola dumerili*), gray triggerfish, and gray snapper (*Lutjanus griseus*). However, there are species for which it will not be possible to generate distribution maps for the entire GOM using the large monitoring database compiled in this study. This will not be possible for coastal species such as ladyfish (*Elops saurus*), common snook (*Centropomus undecimalis*), red drum (*Sciaenops ocellatus*), black drum (*Pogonias chromis*) and sheepshead (*Archosargus probatocephalus*), due to a dearth of encounter data collected using random sampling schemes in Louisiana waters and, to a lesser extent, in Mississippi and Alabama waters (Online Resources 1 and 2). Generation of distribution maps will also not be possible for large pelagic species such as Atlantic bluefin tuna (*Thunnus thynnus*) or white marlin (*Tetrapterus albidus*), which are found both inshore and offshore, but are encountered almost exclusively by the offshore, pelagic observer program (POP). Methodologies should be

Table 4 Confirmation from the literature of some of the spatial distribution patterns predicted in the present study

Functional group/species/life stage	Predicted spatial distribution patterns	Studies confirming these spatial distribution patterns
Younger juvenile red snapper (*Lutjanus campechanus*)	Primarily encountered on the shelves of Texas, Louisiana, Mississippi and Alabama, in the Florida Panhandle region, and near the Dry Tortugas and the Florida Keys, at depths ranging between 20 and 60 m	Gallaway et al. (1999), Szedlmayer and Conti (1999), Karnauskas et al. (2013b), Monk et al. (2015)
Older juvenile red snapper	Has a high probability to be encountered all over the U.S. Gulf of Mexico (GOM) shelf at depths ranging between 40 and ~ 200 m	Szedlmayer and Lee (2004), Wells (2007), Gallaway et al. (2009)
Adult red snapper	Is mainly encountered on the shelf regions of Texas, Louisiana, Mississippi and Alabama where depth varies between 80 and 200 m	Patterson et al. (2001), Mitchell et al. (2004), Gallaway et al. (2009)
Gag (*Mycteroperca microlepis*)	Tends to be encountered all over the West Florida Shelf	Coleman et al. (1996, 2011), SEDAR 33 (2014)
Red grouper (*Epinephelus morio*)	Tends to be encountered all over the West Florida Shelf	Coleman et al. (1996, 2011), SEDAR 42 (2015)
Black grouper (*Mycteroperca bonaci*)	Almost exclusively encountered in the southernmost region of the West Florida Shelf	Bullock and Smith (1991), Crabtree and Bullock (1998)
Goliath grouper (*Epinephelus itajara*)	Almost exclusively encountered in the southernmost region of the West Florida Shelf	Collins and Barbieri (2010), Koenig et al. (2011)
Other shallow water groupers (Representative species: scamp (*Mycteroperca phenax*))	The species belonging to the “other shallow water groupers group”, such as scamp, have a high probability to be encountered all over the edge of the West Florida Shelf, as well as on the edge of the Alabama shelf and in the Flower Garden Banks area	Coleman et al. (1996), Lombardi-Carlson et al. (2012)
Pink shrimp (*Farfantepenaeus duorarum*)	Mainly encountered in the northeastern GOM	Costello and Allen (1970), Bielsa et al. (1983)
Juvenile brown shrimp (*Farfantepenaeus aztecus*)	Is generally encountered in the shallow (0–20 m) areas of the northwestern GOM	Lassuy (1983)
Adult brown shrimp	Adult brown shrimp hotspots are essentially found in the areas of the northwestern GOM where depth ranges between 20 and ~ 100 m	Lassuy (1983)
White shrimp (*Litopenaeus setiferus*)	White shrimp hotspots are almost exclusively found in the northwestern GOM	Muncy (1984)

developed to fit statistical models to monitoring data collected using a mix of monitoring data collected using random, fixed or opportunistic sampling schemes, so as to enable the production of distribution maps for the entire GOM for the coastal and large pelagic species for which distribution maps remain unattainable at present.

We also recommend further research regarding the consistency of monitoring data from different sources, and the sensitivity of distribution maps of functional groups/species/life stages of the GOM to the consideration of different monitoring programs. This could be accomplished by systematically exploring all data from a single source, predicting probability of encounter, and then evaluating how well the model predicts the excluded data. This sensitivity analysis would be particularly important for multiple monitoring programs operating at the same time and place, and failure to predict the excluded data could indicate spatial differences in catchability between monitoring programs. Ultimately, statistical models could be developed that estimate spatial variation in catchability for one or more monitoring programs, and estimates of spatially varying catchability could be used to test whether spatial variation in catchability is substantial or largely insignificant.

Another recommendation for future research pertains to the estimation of fish and invertebrate abundance from data of the large monitoring database for the GOM. In this study, we focused on estimating spatial patterns of probability of encounter. However, many stock assessment and EBFM efforts may be better informed by estimates of abundance. Thus, we recommend testing of statistical models that fit both encounter/non-encounter and abundance samples. In particular, several monitoring programs of the GOM record data in both biomass and numbers (Online Resource 2). We therefore see a need for statistical models that can simultaneously integrate encounter/non-encounter data (as we have used here), count data (e.g., counts of individuals captured by the Southeastern Shrimp Fisheries Observer Coverage Program) and biomass-sampling data (e.g., weights captured by the SEAMAP Groundfish Trawl Survey). One modeling strategy is further testing of geostatistical GLMMs using a compound-Poisson-gamma distribution for biomass, a Poisson distribution for counts, and a logistic regression using a complementary-log–log link for encounters/non-encounters. These three distributions are all derived from the assumption that individuals are randomly distributed in the vicinity of sampling and, therefore, could be fitted within a single GLMM framework. Estimates of abundance would then allow estimates of biomass indices (for use in fisheries stock assessment) to quantify the biomass of predators per prey (for functional response models) or shifts in distribution (using center-of-gravity measures of distribution).

Research recommendations

Our research recommendations, which aim to benefit stock assessments and EBFM in the GOM, can be grouped into three categories: (1) improving current monitoring programs and designing new monitoring programs; (2) guidance for more comprehensive use of monitoring data; and (3) sharing data. Some of our recommendations arise from findings of the previous sections of the present study, while the other recommendations result from the “Gulf of Mexico Ecosystem Modeling Workshop” or “GOMEMOw”. GOMEMOw took place at the Rosenstiel School of Marine an Atmospheric Science/University of Miami, Florida, in January 2016, and involved the authors of the present study, as well as other ecosystem modelers and empiricists and fisheries managers, fishing industry representatives and NGO representatives of the GOM (Online Resource 7).

Improving current monitoring programs and designing new monitoring programs

We have four recommendations for improving fish and invertebrate monitoring in relation to stock assessments and EBFM in the GOM: (1) restoring and expanding discontinued monitoring programs of the GOM; (2) developing spatially and temporally explicit fisher quantitative video input; (3) carefully considering the initial design and protocol of monitoring programs; and (4) organizing the systematic collection of stomach content data in the GOM.

Restoring and expanding discontinued monitoring programs of the GOM Among the monitoring programs presented in this study, some are limited in temporal scale and are no longer active. For example, the Florida Fish and Wildlife Research Institute (FWRI) Purse Seine Survey was implemented only from 1997 to 2004. However, the cessation of this survey is not a concern; Florida has two other seine-based, fisheries-independent programs (the FWRI Bay Seine Survey and the FWRI Haul Seine Survey), which are still active and sample the bays that used to be sampled by the FWRI Purse Seine Survey. By contrast, the episodic nature of the Northern Gulf of Mexico Continental Slope Habitats and Benthic Ecology Study Survey (DGOMB) and the cessation of the Florida State University (FSU) Estuarine Gag Survey in 2009 are disadvantageous. The DGOMB survey, which took place during the summer months of the period 2000–2002 in the offshore areas of the GOM, is a unique source of data for small invertebrate meiofauna, small infauna and similar animals. Yet, in addition to having been short-lived, this survey was conducted at a limited number of sites. Reinstating the DGOMB survey and expanding it to the inshore regions of the GOM would provide critical data to assist research in the GOM, given the strong importance of benthic dynamics to the ecosystems of the GOM (Gaston et al. 1997; Brown et al. 2000; Chesney and Baltz 2001). The FSU Estuarine Gag Survey collected data for younger juvenile gag using an otter trawl and a fixed sampling method in the eight regions of West Florida where Ingram et al. (2013) reported the life stage to be consistently found. Resuming the FSU Estuarine Gag Survey would provide valuable data for younger juvenile gag, since this dataset was combined with FWRI and NOAA Fisheries monitoring surveys to produce a young-of-the-year index of abundance in the gag stock assessment (Ingram et al. 2013).

Developing spatially and temporally explicit fisher quantitative video input GOMEMOw identified cooperative studies with fishers as a potential way to improve monitoring data in the GOM. Spatially and temporally explicit fisher quantitative video via video cameras could provide critical input on reef fish spatial distribution patterns and behavior. In the GOM, the fishing industry frequently offers to contribute to monitoring fish populations for assisting fisheries stock assessments (Grüss et al. 2016a), and fisher involvement can provide invaluable local knowledge. Some fishers could be provided with a submersible rotating video system (SRV) similar to that developed in Koenig and Stallings (2015) for video monitoring of reef fish abundance. SRVs are simple tools, which provide quantitative quadrat data without the use of bait. If fishers dropped video cameras mounted to the SRVs on their fishing spots (with loose geographic coordinates so the exact location of fishing spots is not known) for 5 min, quantitative data on species composition, co-occurrence and relative abundance could be derived. Federal and State agencies would benefit from the video data, as it would save them expensive field time. If fishing industry groups invested in this approach, they would also benefit from contributing to stock assessments and fisheries management. This approach could be particularly useful for the recreational fishing industry for which only a few georeferenced datasets are currently available (Online Resources 1 and 2).

Carefully considering the initial design and protocol of monitoring programs For a number of monitoring programs of the GOM, important changes in monitoring design and protocol have occurred over time (e.g., the SEAMAP Gulf of Mexico Inshore Bottom Longline and Vertical Line Surveys; Online Resource 2). If new monitoring programs are initiated in the GOM during the coming years, their initial sampling design and protocol should be carefully considered. Changes to sampling designs and protocols have the potential to jeopardize the usefulness of monitoring data for developing abundance indices. While calibrations can sometimes be employed to account for changes in sampling designs, a better approach is to carefully reflect on the initial sampling design and protocol, considering all the potential future aspects and constraints of the monitoring program of interest (e.g., funding shortages).

Organizing the systematic collection of stomach content data in the GOM The lack of diet data as a critical issue for ecosystem modeling in the GOM. Only a few monitoring programs of the GOM currently collect fish stomachs opportunistically (Table 1). Diet data represent a critical need for many ecosystem models (e.g., EwE and Atlantis applications) since the simulation of trophic interactions is the most critical feature of most ecosystem models (Plagányi 2007; Christensen and Walters 2011; Grüss et al. 2016a). In addition, increased understanding of trophic interactions could provide justification for ecosystem considerations within stock assessment models, such as predation mortality. Many monitoring programs of the GOM have the potential to collect fish stomachs (Table 1). Therefore, we recommend that, every year, an institute of the GOM takes inventory of the species and life stages for which diet information is critically needed, and requests relevant monitoring programs to collect the data needed. To facilitate this endeavor, the encounter/non-encounter estimates of the monitoring datasets of the GOM could be analyzed to determine the monitoring programs that most frequently encounter the different fish and invertebrate species and life stages of the GOM.

Guidance for more comprehensive use of monitoring data

Our inability to produce average distribution maps for the entire GOM for a number of coastal and pelagic species using the large monitoring database reveals the need to develop statistical methodologies enabling mapping using the diversity of monitoring data currently available for the GOM. More specifically, future studies should develop statistical models that can be fitted to monitoring data collected using a mix of monitoring data collected using random, fixed or opportunistic sampling schemes.

The application of the large monitoring database in the present study was limited to the production of average distribution maps for fish and invertebrates. However, many fundamental questions that need to be addressed in the GOM pertain to specific years or periods of time. These questions include the consequences of important events (e.g., the *Deepwater Horizon* oil spill or the implementation of individual fishing quotas for grouper and snapper species) on the spatial distributions of economically important fish and invertebrate species, or the impacts of future climate change on fish spatial distributions. To explore the impacts of future climate change on fish spatial distributions, statistical models integrating environmental covariates (e.g., sea surface temperature) as well as spatio-temporal variation (reflecting changes in spatial distributions among years) could be fitted to monitoring data for the GOM; the integration of spatio-temporal variation in statistical models would be particularly useful to detect changes in fish and invertebrate spatial distributions over time, either directional (in response to climate; Pinsky et al. 2013) or interannual (in response to size-structured effects; Thorson et al. 2017).

The review of the sampling characteristics and protocols of GOM monitoring programs (Online Resource 2) revealed important changes in technology or instrumentation within many individual monitoring programs through time and, therefore, raise the issue of changes in catchability within individual monitoring programs through time. To produce more reliable abundance indices for assessed species of the GOM, changes in catchability through time should be quantified and monitoring programs should be calibrated. To be able to calibrate monitoring programs of the GOM (at least the major ones, such as the SEAMAP Groundfish Trawl Survey), metadata on changes in the methodologies of monitoring programs over time should be compiled and, in parallel, calibration experiments (i.e., using two different sampling methods at the same time and place) should be carried out to estimate calibration ratios. Such studies have been conducted in other marine regions (e.g., the Northeast U.S. region; Miller et al. 2010).

Sharing data

To facilitate future studies assisting stock assessments and EBFM projects in the GOM, the large monitoring database we compiled should be shared online. We recommend the development of a web-service similar to that designed for the NMFS—UM Dry Tortugas Visual Census Survey (SEFSC 2016); this web-service would provide the user with the monitoring data available for specific species, life stages and areas of the GOM, through a series of simple queries. This service could use a fixed and documented Application Programming Interface (API) so that software for machine-to-machine data transfers can then be developed. However, due to the confidentiality of most of the fisheries-dependent datasets of the GOM, the following restrictions would apply to those data: (1) encounter/non-encounter rather than abundance estimates at aggregated spatial domains (to eliminate concerns over confidentiality) would be provided; and (2) the name of monitoring programs providing data would not be revealed.

Here, we focused on the U.S. GOM for practical reasons. However, an increasing number of research projects are being initiated for the entire GOM Large Marine Ecosystem (which includes the Mexican and Cuban GOM). Moreover, Atlantis-GOM, which is a pioneering ecosystem model of the GOM, simulates dynamics in the entire Large Marine Ecosystem and, therefore, needs monitoring data for the southern (i.e., Mexican and Cuban) GOM for its parameterization, calibration, and validation. Therefore, we recommend future studies to compile a monitoring database for both the U.S. and southern GOM. However, this endeavor will be highly challenging. For example, in the Mexican GOM, few fisheries-independent surveys have been conducted and documentation from surveys is scarce. At first glance, the best fisheries-independent data available from the Mexican GOM are from a series of shrimp trawl cruises from the early 1980s, which are provided in a PhD dissertation (Sanchez-Gil 2009) (Joel G. Ortega Ortiz, University of South Florida, personal communication).

The focus of the present study is on monitoring data, which can be employed to produce distribution maps for fish and invertebrates for some ecosystem models, among other objectives. However, to allocate the biomasses of fish and invertebrates over space, most ecosystem models rely not only on distribution maps, but also on defined movement patterns (e.g., Chagaris 2013; Ainsworth et al. 2015). To define movement patterns, ecosystem modelers generally use the results of tagging studies; for instance, the parameterization of the movement rates of red grouper and red snapper in the WFS Reef fish EwE model relied on tagging data collected by FWRI (Chagaris 2013). Many tagging projects have been or are currently implemented in the GOM. For example, some of the for-hire surveys of the GOM tag live releases, as does the Alabama Marine Resources Division in Alabama waters. Moreover, there is now a large acoustic monitoring array across the U.S. GOM (Currier et al. 2015). We recommend future studies to compile a database storing all the tagging data of the GOM to facilitate the parameterization of movement patterns in ecosystem models of the GOM as well as other research endeavors necessitating tagging data, including stock assessments.

Concluding remarks

Our inventory of monitoring programs of the GOM revealed that a large number of fisheries-independent and fisheries-dependent programs have been carried out in the GOM, most of which (n = 62; 85%) are still active (Online Resources 1 and 2). We identified a total of 73 monitoring programs for the GOM, which greatly differ in their sampling protocols and characteristics, region sampled and seasonality. Most of these programs are fisheries-independent (n = 49; 67%). One distinctive feature of monitoring programs of the GOM is that they include a fair number of fisheries-independent surveys conducted almost year-round (Fig. 3), contrasting with most other marine regions of the world (e.g., the Eastern English Channel; Bourdaud et al. 2017; the Northwest Atlantic; Politis et al. 2014). Another distinctive feature of these programs is that they include fisheries-dependent programs sampling recreational fisheries, which is critical since, in the GOM, recreational fisheries exert higher fishing mortality rates on many stocks than commercial fisheries (Adams et al. 2004; Coleman et al. 2004). Most of the monitoring programs of the GOM use random sampling schemes (n = 45; 62%) and record the geographic coordinates (n = 58; 79%). We incorporated most of these types of monitoring programs into a large monitoring database for the GOM, which we used to fit geostatistical models to then map the spatial distributions of fish and invertebrates of the GOM. The large monitoring database for the GOM represents a goldmine of information for single-species stock assessments and EBFM projects and should be viewed as a dynamic platform that should be regularly updated as new monitoring data become available (Grüss et al. 2016a).

Despite their richness and diversity, monitoring programs of the GOM would greatly benefit from improvements and better practices in terms of use and data sharing. We made several recommendations in these regards. A major sampling recommendation is the development of a coordinated strategy for collecting diet information by existing GOM monitoring programs for advancing EBFM.

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