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# Long-term monitoring informs data-poor marine species in the northern Gulf of Mexico

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**Abstract.** Fisheries monitoring programs around the world are often designed to provide information on a wide range of species that come into contact with the program gear(s). Such programs may provide untapped abundance and distribution data for species of greatest conservation need (SGCN) and other rare or data-deficient species. We examined >30 years of fish sampling data from coastal Louisiana and found that 13 of 18 SGCN marine fishes were represented in existing routine monitoring data. Although some species were rarely reported, >100 records were available for seven species, with some species being reported several thousand times. Using these records, we were able to provide species-specific information about gear, season, location and timing for several marine fishes that were considered largely unknown. Given the paucity of information available for these species and the rapidly changing Louisiana coast, these biogeographic data may be important in the development of future conservation and management programs.

**Keywords:** Louisiana, marine fishes, species of greatest conservation need.

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## Introduction

Monitoring wild fish populations provides a multitude of benefits, many of which are tied to information regarding species range, distribution and abundance that can then be used to inform management programs. For example, long-term monitoring of fish populations can advance understanding of spatial and temporal patterns of species distribution and change (McClelland *et al.* 2012; Ho *et al.* 2020), inform conservation (Ojeda-Martínez *et al.* 2007), and provide reference information to guard against a shifting baseline (Magurran *et al.* 2010). Long-term monitoring of fishes takes place across the globe; for example, the International Bottom Trawl Survey (IBTS) in the North Sea (ICES 2012) and the AIMS (Australian Institute of Marine Science) Long-Term Monitoring Program[1] in Australia have collected fish data for decades. In the USA and elsewhere, fishery-independent monitoring programs (FIMP) are usually considered *target* or *surveillance* monitoring (Nichols and Williams 2006). Target monitoring is often characterised by data collection specific to one or a few hypotheses, whereas surveillance monitoring tends to be more of an omnibus sampling program that generates data to be used opportunistically as needs arise (Nichols and Williams 2006). The reality of fish monitoring is that most programs are a combination of targeted and surveillance monitoring. Often one or more gear(s) are used because of their high selectivity for some target species (usually recreational or commercial species of interest); however, many gears have some selectivity for a wide range of species and can generate data for non-specific uses (Franco *et al.* 2012; Pasquaud *et al.* 2012). Regardless of the monitoring program, many fishes remain poorly detected or absent from sampling, which has led to an imbalance in biological and ecological knowledge about individual fish species (Maxwell and Jennings 2005).

Although fishes have been monitored around the world in myriad ways that reflect the diversity of species, habitats and logistical and financial restrictions, the value of fishery-independent monitoring is widely acknowledged. For example, in the Pacific, fishery-independent surveys provided better management confidence and economic benefits over fishery-dependent data alone in the Torres Strait rock lobster, *Panulirus ornatus* (Fabricius), fishery (Dennis *et al.* 2015). In the Mediterranean Sea off Spain, fishery-dependent and fishery-independent data were combined for optimal information for elasmobranch species (Pennino *et al.* 2016); fishery-dependent data were found to be predictive on the basis of environmental

[1]https://www.aims.gov.au/docs/research/monitoring/reef/reef-monitoring.html.

 

correlates, whereas fishery-independent data were demonstrated to better describe spatial presence–absence (PA). Finer-resolution data may be available from FIMPs in countries with greater monitoring resources; however, there is still the potential for valuable species and habitat information to be generated with limited resources and simple monitoring designs (Joseph *et al.* 2006; Zhao *et al.* 2017).

USA state resource agencies often carry out FIMPs to generate long-term abundance and distribution data that can be incorporated into stock assessments of commercially and recreationally exploited species. For example, the Louisiana Department of Wildlife and Fisheries (LDWF) employs a diversity of gear in their long-term sampling program to maximise capture efficiency for targeted species and detection probability for as many additional species as possible (LDWF 2015). The standardised FIMP for marine and coastal fishes used by LDWF is based on methods developed during the Cooperative Gulf of Mexico Estuarine Inventory and Study (Perrett *et al.* 1971), and was fully implemented by 1986 (see LDWF 2015, for additional description). The finfish sampling program is based on a variety of gear types across a range of habitats to provide information on different life stages of estuarine-dependent fishes. The most common gears used are a 15.24-m bag seine, a 228.6-m experimental gill-net, a 228.6-m trammel net, a 4.88-m inshore trawl, a 1.83-m inshore trawl, and a 6.10-m nearshore trawl. Other gears have been used over time (e.g. electrofishing) and are also present in the dataset. Many gears are used year-round, whereas others are fished during specific seasons when the gear is safe to deploy and targeted organisms are available. For full programmatic details, see LDWF (2015).

In Louisiana's estuaries, many abundant species with high capture probabilities are well represented in the long-term FIMP database, e.g. red drum, *Sciaenops ocellatus* (Linnaeus), black drum, *Pogonias cromis* (Linnaeus), and Atlantic croaker, *Micropogonias undulatus* (Linnaeus). However, sampling efforts provide collection data on all species encountered by the gear, including data that may not be of immediate interest to managers and therefore goes unanalysed. Louisiana's Wildlife Action Plan (WAP; Holcomb *et al.* 2015) includes species of greatest conservation need (SGCN) for a wide range of taxa, including 18 marine fishes. Fishes are assigned SGCN status following an extensive review of literature and research and input from stakeholders. The process follows congressional and Association of Fish and Wildlife Agencies (AFWA 2012) guidance to determine distribution and abundance of wildlife and fish species, particularly those with low or declining populations or that may be indicator species. Louisiana's SGCN species were originally listed in 2005 and updated in 2015 (Holcomb *et al.* 2015). In addition to *G* (global) and *S* (state) rankings, the 2015 revision also prioritises species into three tiers on the basis of decreasing needs for conservation. Although the study of SGCN fishes is common (and related to the lack of information on these species), it is now being recognised that not only might SGCN designations be improved with more data, but that SGCN fishes also represent an understudied group of species that may yield insights on fish assemblage and habitat changes on the basis of compilations of existing data (Faucheux *et al.* 2019). For example, Sindt *et al.* (2012) studied 84 wadeable streams to generate predictive models for seven SGCN fishes, and Schloesser *et al.* (2012) evaluated different gear types and their effect on detection probabilities for imperilled riverine fishes. Despite these nascent efforts, few studies have reported on SGCN fishes, and even fewer on marine fish SGCN.

Analyses of monitoring data in the context of SCGN could provide a critical first step towards understanding species distributions and abundances over time. In addition, given the ecological significance of predicted changes to coastal habitats in Louisiana (Couvillion *et al.* 2011) and other globally threatened coasts, an accounting of marine fish SGCN could prove to be incredibly valuable as coastal management plans are developed and habitats are prioritised for restoration. Both PA and abundance information could directly inform the design of future fieldwork to improve our understanding of these understudied marine fishes. Consequently, our objective was to use several decades of FIMP data collected across coastal Louisiana to advance our understanding of the distribution and abundance of marine fish SGCN. Specifically, we sought to determine (1) representation of different SGCN in the dataset, (2) seasonal patterns of occurrence and, when possible, abundance (in the form of catch per unit effort; CPUE), (3) associations between specific sampling gear and specific species, and (4) spatial and/or temporal patterns of species occurrence.

## Materials and methods

### *Data usage*

We examined >30 years of existing FIMP data for marine fish SGCN sampled by LDWF (Fig. 1). Initial analyses were designed to extract and analyse species-specific information such as *month*, *gear* and *location* of captures. For uncommon species (<100 samples), we retained all samples and did not estimate effort because so few individuals were captured; however, for the six most commonly sampled SGCN species, we did account for effort. Although effort data should be consistent across years (each gear has its own deployment schedule determined by the sampling program), we still extracted effort from the sampling because of both year-to-year variability in effort and changes in effort due to changes in sample sites. For example, hurricanes and other disruptions resulted in years with a lower effort, whereas addition of sites over time resulted in long-term effort increases. Effort was defined here as a sampling event that used standardised methodologies, such as, for example, a standardised trawl sampling event. Catch was defined as the abundance of a given species within a sampling event. The following four of the six most common species were most often reported in seine gear: bayou killifish (95% of samples), diamond killifish, (95%), saltmarsh topminnow, (87% of samples) and chain pipefish, (62% of samples). Southern puffer and violet goby were both collected in trawls 90% of the time they were reported. CPUE was calculated using those most common gear for each respective species, as described above.

We had opportunistic sampling records going back to the 1960s, and although we initially evaluated SGCN in the entire dataset, we truncated our data analyses to begin in 1986 when the sampling program was standardised. Excluding data before this time period should have reduced potential effects of gear changes and other sampling inconsistencies, and generally produced results consistent with the contemporary sampling program.

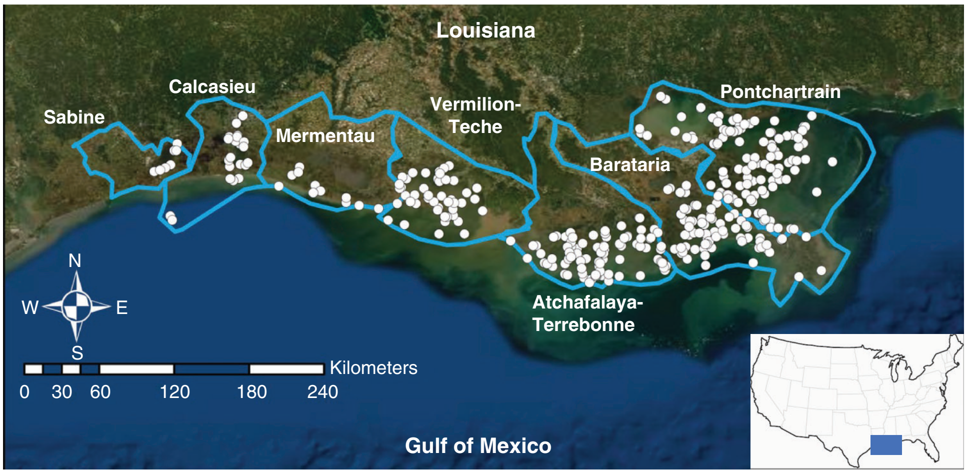


**Fig. 1.** Map of sampling sites that contributed data to the current study. All sampling took place in coastal waters of Louisiana, USA. White dots indicate locations of sampling that produced at least one species of greatest conservation need (SGCN) fish used in this study; however, most sampling sites were samples numerous times and many produced multiple SGCN fishes. Blue polygons outline major coastal estuaries.

### *Data analysis*

So as to model (non-linear) change in individual species CPUE over time, we used generalised additive models (GAMs) for the six species with the most data (we were hesitant to make long-term inferences for species that were not well represented). GAMs serve as an appropriate model for our analysis because their non-parametric flexibility permits the data to determine the shape of the model, as opposed to parametric models where the shape of trends is constrained by the model (Yee and Mitchell 1991). This results in the relationship between explanatory and response variables being estimated as a smoothing function. The ability of GAMs to detect non-linear trends and be applied to multiple distributions was required, given the variability and unknown distributions associated with SGCN sampling (Guisan *et al.* 2002). GAMs are applicable to any likelihood-based regression and served in this analysis to automatically estimate the non-linear effect of our covariate, time (*years*; Hastie and Tibshirani 1986). Our models were fit with a normal distribution and the thin plate spline smoothing function (Wood 2003), which serves as the most general and widely applicable spline (Pedersen *et al.* 2019). These splines are most appropriate for investigating unknown trends where seasonality is not expected, while still maintaining statistical integrity and avoiding problems with knot placement. The basis dimension (i.e. number of knots) was fixed at $k = 5$ to prevent overfitting.

Our model had the form

$$g(E(Y)) = \alpha_n + \sum\nolimits_{j=1}^{J} f_j(x_{jn})$$

where $E(Y)$ is the expected CPUE, with a normal distribution and an identity link function $g()$, $\alpha_n$ is the intercept for each group (species, $n$), and $f_j$ is the smooth function of the covariate (years, $j$) $x_{jn}$, for each species. Time was the only regressor included in our GAMs, so as to isolate its effect on CPUE. GAMs were fit with the restricted maximum-likelihood methodology to further penalise overfitting and provide a more optimal handling of variability (Wood 2011). Further, GAMs were evaluated on the basis of residuals and effective degrees of freedom to ensure reasonable fitting under the constraint of $k = 5$. All models were fit in the R Statistical Programming Language and Environment (R Core Team 2020) with the mgcv package (Wood 2011).

## Results

Of the 18 marine fish SGCN listed in the Louisiana WAP, 13 species are on record as having been captured in FIMP of the LDWF (Table 1). The database included 6768 samples that contained at least one capture of these 13 SGCN, with a total of 42 777 individual observations of SGCN coastal fishes. By species, the total number of individual species collected ranged from five (smalltooth sawfish and gold brotula) to 15 787 (southern puffer; Table 2). Species records were available from 1966 to 2018, and although we report the total numbers from the entire dataset, subsequent analyses are focussed on the more recent period of standardised sampling (1986–2018).

### *Gear*

A total of 17 gears detected fishes in the dataset, although several gears detected multiple SGCN; for example, individual fish were reported in one of six different mesh-size panels in experimental gill-nets. For our analyses, we pooled specific gear into seven common gear types (Fig. 2). Among these, the 15.24-m bag seine ($n = 7419$) and 4.88-m otter trawl ($n = 6220$) had the most samples containing SGCN, with all other gear containing 502 or fewer total captures of SGCN coastal fishes. The cast net, wing net and gill-net encountered the fewest SGCN fishes.

### *Timing of capture*

Although not all sampling gear are deployed uniformly throughout the year, some sampling did take place each month. Across the dataset, November yielded the greatest number of samples

**Table 1. List of 18 marine fish species of greatest conservation need (SGCN) as provided in the Louisiana Wildlife Action Plan (2017)**

Tiers, G-rank (global status rank), and S-rank (subnational status rank) are defined in the WAP and included here for reference. The 'Data Available?' column indicates whether the species has been captured and therefore data are available from the Louisiana Department of Wildlife and Fisheries fishery-independent sampling program; 13 of 18 species have some amount of data available for study. The relative captures represent the number of sampling events in which the species has been present; rare species have been sampled less than 100 times; common species have been sampled more than 100 times but less than 1000 times; abundant species have been sampled more than 1000 times

| Common name, scientific name | G-rank | S-rank | Data available? | Sampling encounters |
|---|---|---|---|---|
| Tier I | | | | |
| Smalltooth sawfish, *Pristis pectinata* | G1G3 | S1 | Yes | Rare |
| Saltmarsh topminnow, *Fundulus jenkinsi* | G3 | S3 | Yes | Abundant |
| Texas pipefish, *Syngnathus affinis* | G1 | SU | No | None |
| Goliath grouper, *Epinephelus itajara* | G2 | S1 | No | None |
| Tier II | | | | |
| Diamond killifish, *Adinia xenica* | G5 | S4 | Yes | Abundant |
| Bayou killifish, *Fundulus pulvereus* | G5 | S4 | Yes | Abundant |
| Opossum pipefish, *Microphis lineatus* | G4G5 | SU | No | None |
| Chain pipefish, *Syngnathus louisianae* | GNR | S4 | Yes | Abundant |
| Tier III | | | | |
| Tarpon, *Megalops atlanticus* | G5 | S3 | No | None |
| Gold brotula, *Gunterichthys longipenis* | GQ | SU | Yes | Rare |
| Dwarf seahorse, *Hippocampus zosterae* | GNR | SU | Yes | Rare |
| Large-scaled spinycheek sleeper, *Eleotris amblyopsis* | G5 | S4 | No | None |
| Emerald sleeper, *Erotelis smaragdus* | GNR | SU | Yes | Rare |
| Frillfin goby, *Bathygobius soporator* | GNR | S4 | Yes | Rare |
| Violet goby, *Gobioides broussonnetii* | G5 | S4 | Yes | Common |
| Broad flounder, *Paralichthys squamilentus* | GNR | SU | Yes | Rare |
| Southern puffer, *Sphoeroides nephelus* | G5 | S5 | Yes | Abundant |
| Lemon shark, *Negaprion brevirostris* | GNR | S3 | Yes | Common |

containing any SGCN fishes ($n = 6440$), whereas April samples contained the fewest ($n = 1407$). Bayou killifish, diamond killifish and saltmarsh topminnow all showed the highest frequency of occurrence in fall and winter samples, whereas southern puffer was detected most often in the summer and fall (Fig. 3). Chain pipefish was encountered consistently uniformly throughout the year, whereas violet goby was more abundant in spring samples than in samples from the rest of the year. Other species were sampled too infrequently to infer seasonal patterns, although for these species, detection and non-detection may be a more relevant metric than increases or decreases in sample occurrence.

**Table 2. Total number of detections (*N*), total number of samples detecting at least one individual of the species, and the peak month(s) and most common gear(s) associated with the 13 SGCN marine fishes**

NA indicates that there was not enough data to confidently report

| Common name | *n* | Samples | Peak month(s) | Most common gear |
|---|---|---|---|---|
| Southern puffer | 15 787 | 2030 | June | Trawl |
| Diamond killifish | 14 157 | 1044 | December | Seine |
| Bayou killifish | 6293 | 844 | December | Seine |
| Chain pipefish | 4019 | 1804 | October | Seine/trawl |
| Saltmarsh topminnow | 1501 | 359 | November/ December | Seine |
| Violet goby | 779 | 561 | April | Seine/trawl |
| Lemon shark | 103 | 62 | October | Gill-net/ trammel net |
| Frillfin goby | 63 | 24 | October/ November | Seine/trawl |
| Broad flounder | 45 | 17 | March | Seine |
| Emerald sleeper | 14 | 13 | NA | NA |
| Dwarf seahorse | 6 | 3 | NA | NA |
| Smalltooth sawfish | 5 | 2 | NA | NA |
| Gold brotula | 5 | 5 | NA | NA |

## *Capture locations*

All coastal basins in Louisiana reported some occurrence of marine fish SGCN. Although the larger basins (Barataria Bay, Calcasieu, Lake Pontchartrain, Terrebonne and Vermilion-Teche) reported the most occurrences of SGCN fishes, some species were frequently detected in basins where few other species were found. Capture locations varied among species (Figs 4, 5); for example, although both chain pipefish and diamond killifish were considered abundant ($n > 1000$ samples), chain pipefish was found in nearly all basins in coastal Louisiana, whereas diamond killifish was absent from three basins.

When examined over time (Fig. 5, Supplementary materials Tables S1–S6, available at the journal's website), some spatial patterns emerged. During the start of the sampling timeframe (1986–1989), SGCN fishes were sampled in more major basins (6 of 6), and more different species (8 of 9) were sampled in the estuaries, notably Calcasieu (Table S3), the westernmost coastal area of the state. The period 1990–2009 was characterised by SGCN species being captured more often in the Terrebonne and Vermilion-Teche basins and relatively less in the other four basins. During the most recent period from 2010 to 2018, SGCN species again appeared more widespread among basins, similar to the earliest time period.

## *Temporal trends*

The GAM analyses indicated the factor *year* was estimated as a significant smooth ($P < 0.05$) for four of the six species, suggesting significant changes in the CPUE of these species sampled over time (Fig. 6). Violet goby and chain pipefish were the

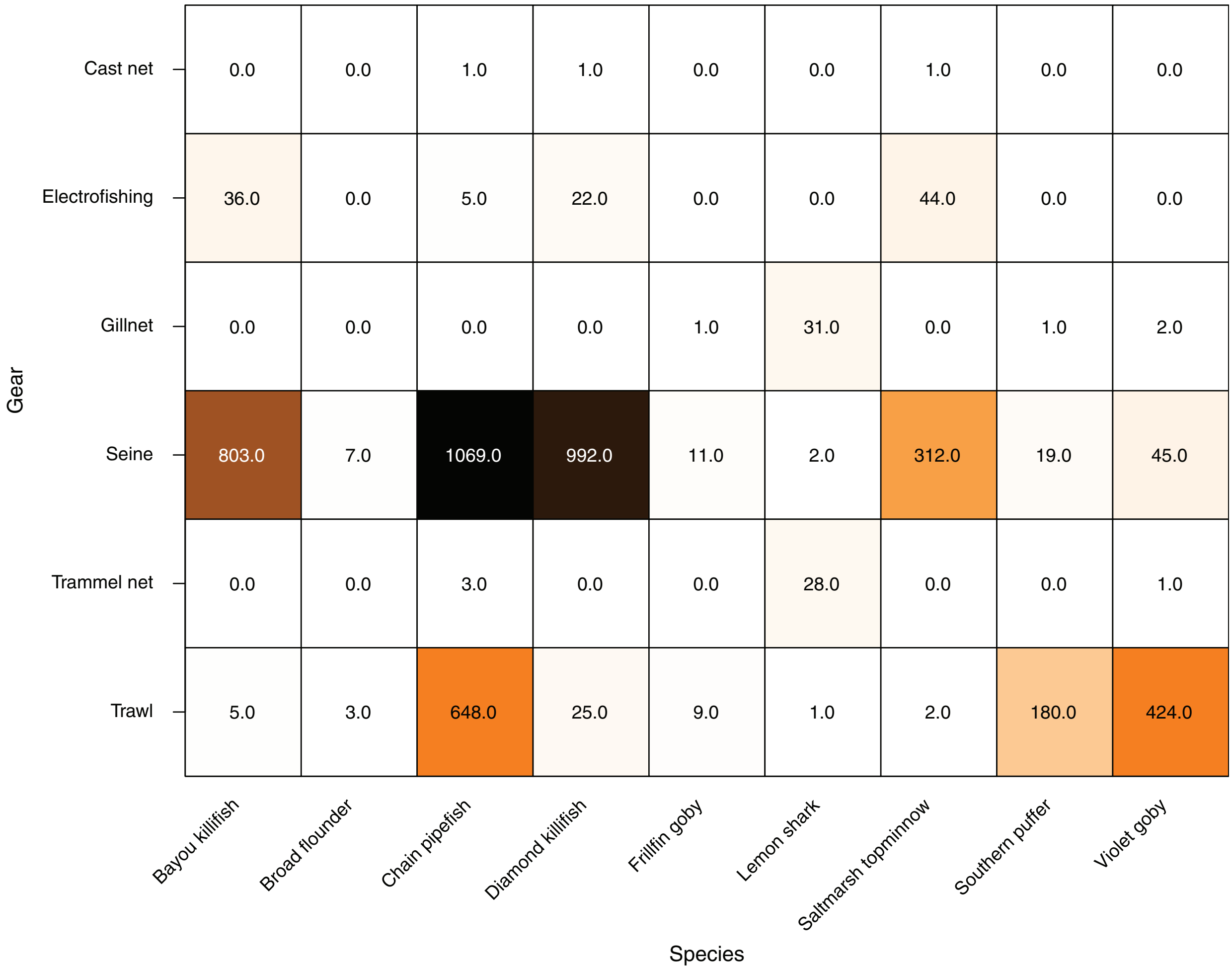


**Fig. 2.** Matrix plot showing combinations of species encounters by gear. Numbers in the matrix represent the number of total samples (from 1986 to 2018) encountering a specific SGCN in a specific gear. Cell colours correspond to the numbers; lighter colours indicate fewer samples, and darker colours indicate a larger number of samples.

two species with non-significant temporal relationships ($P = 0.25$ and $P = 0.36$). Trends for both species were likely to be non-significant because of the variability in year-to-year CPUE, because variations from higher CPUE to successive near-zero values are likely to have weakened the effect of *year* as a smoother. The GAMs detected long-term decreases in bayou killifish, diamond killifish and southern puffer over three decades. Although both killifish species have been encountered in several samples in recent years (Fig. 6), southern puffer has not been caught in sampling since 2010. This decline and disappearance of southern puffer may be due to a shift in sampling stations that took place in the mid-1980s, while the monitoring program was becoming standardised (and possibly because of the fact that Louisiana is at the edge of the species distribution where population fluctuations may be large). Saltmarsh topminnow was the only species to show a significant increase in CPUE over the past 30 years, with an exponential increase especially noticeable in the current decade. GAMs were not only successful in presenting the long-term trends, but their flexibility sufficiently captured the non-linear and variable nature of fish observances.

## Discussion

Species of greatest conservation need are often classified as such because they are data-deficient, and we lack understanding about their basic ecology and distributions. However, this study demonstrated that 72% (or 13 of 18) of SGCN fishes and their associated locations were represented in a public, state-agency long-term monitoring database. In fact, 7 of 13 species encountered were sampled in every month of the year (pooled over multiple years), suggesting possible year-round residency and persistent populations. Further, we considered 5 of the 13 species abundant, as defined by being represented in >1000 samples over several decades of sampling, and none exhibited substantial declines in sample numbers through time that would have suggested spatially extensive population problems across the coast.

### *Spatial and temporal trends*

Long-term sampling suggested some seasonality of occurrences, both species-specific patterns for some species and the larger, overall seasonality of more SGCN fishes collected in the fall. Higher fall catches could be explained by juveniles having

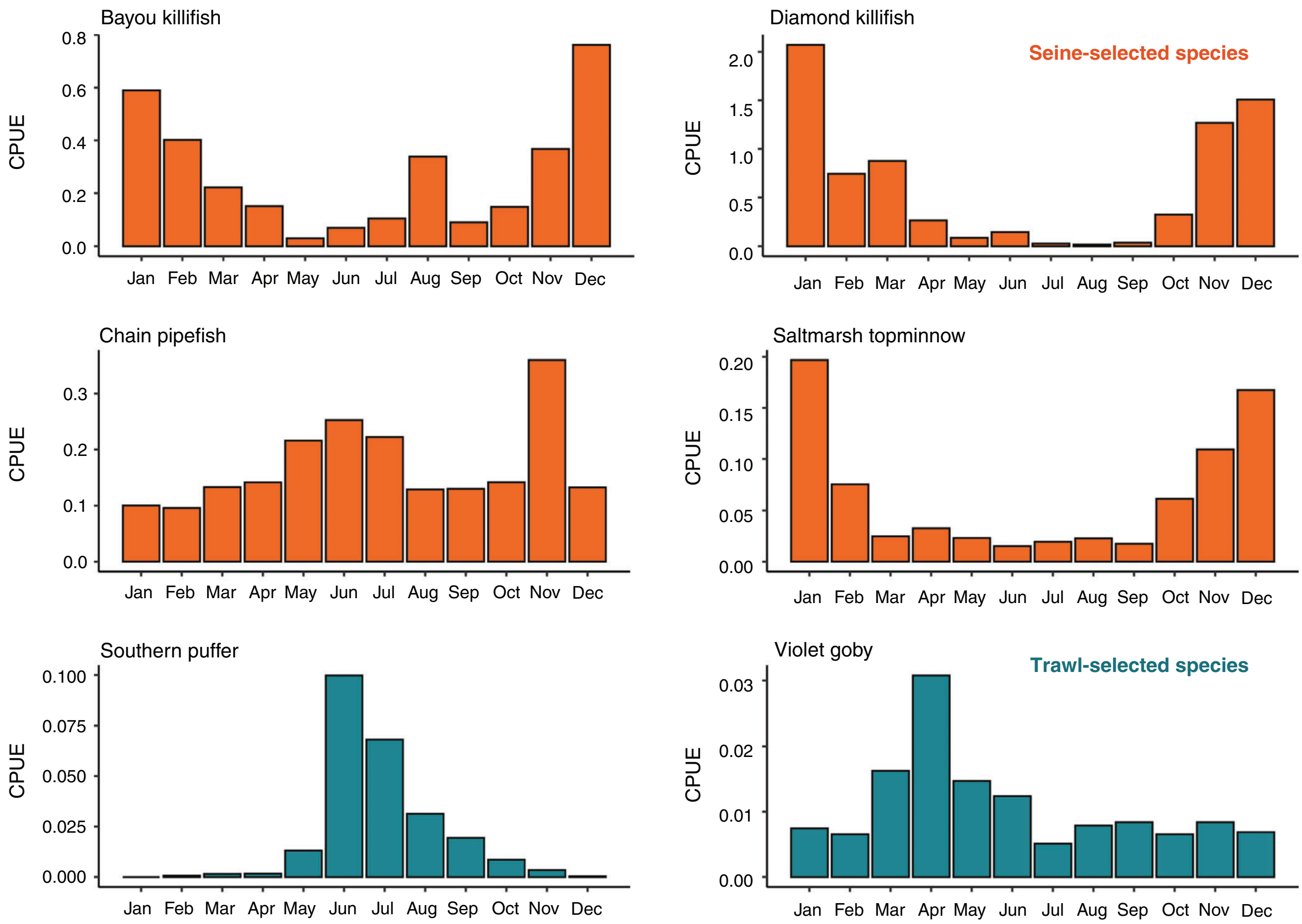


**Fig. 3.** Monthly catch per unit effort (CPUE; pooled across years from 1986 to 2018) of sampling events reporting the six most common marine fish SGCN. Fishes with a greater CPUE show some seasonal patterns, whereas other species are infrequently encountered. Species data displayed in orange indicate seine-selected species, and species data displayed in teal indicate trawl-selected species.

had a full growing season and being large enough by fall to recruit to the sampling gear, although size data would be needed to further support this idea. Some species (e.g. lemon shark, *Negaprion brevirostris* [Poey]) may use inshore habitats only for part of the year or part of their life cycle, and, as such, it would not be expected to encounter them without considering species-specific patterns. Some marine SGCN were basin-specific, but most were widespread across coastal Louisiana. Our findings suggest that SGCN may be more widespread than previously considered, albeit with substantial differences in local occupancy and abundance.

We used GAMs because we were not testing any hypotheses about species occurrences over time and simply wanted a flexible model that could pick up on any (non-linear) changes over many years of sampling. In addition, we needed one model that could be adapted to several datasets with different trends, a purpose GAMs are well suited for with their non-parametric base. Whereas other time-series models such as ARIMA models expect evenly spaced data, the smoothing function of GAMs allowed our models to handle missing years where no effort was recorded by pooling estimates to a mean function value (Simpson 2018; Pedersen *et al.* 2019). Other time-series models, such as dynamic linear models, were not used for this analysis because we were interested in identifying long-term, general trends, as opposed to more responsive methods that estimate at shorter scales. In summary, our data were not a good fit for the model assumptions for ARIMA, temporal covariance structures, or dynamic linear models. Although the majority of our species-specific GAMs showed a statistically significant smoothing function, this is more a result of minor non-linearities that are likely to be present in any fish sampling and not the result of a rigorous trend-detection technique. In fact, although some species have shown declines over time (e.g. bayou killifish, diamond killifish, and southern puffer), most species were still sampled at low levels over the decades of records that we analysed, whereas saltmarsh topminnow displayed an increase in CPUE over time.

### *Changing coast – changing distributions?*

Changes in coastal marine fish species distributions can be expected or unexpected, depending on the location. However, in coastal Louisiana, habitats have been changing rapidly for the

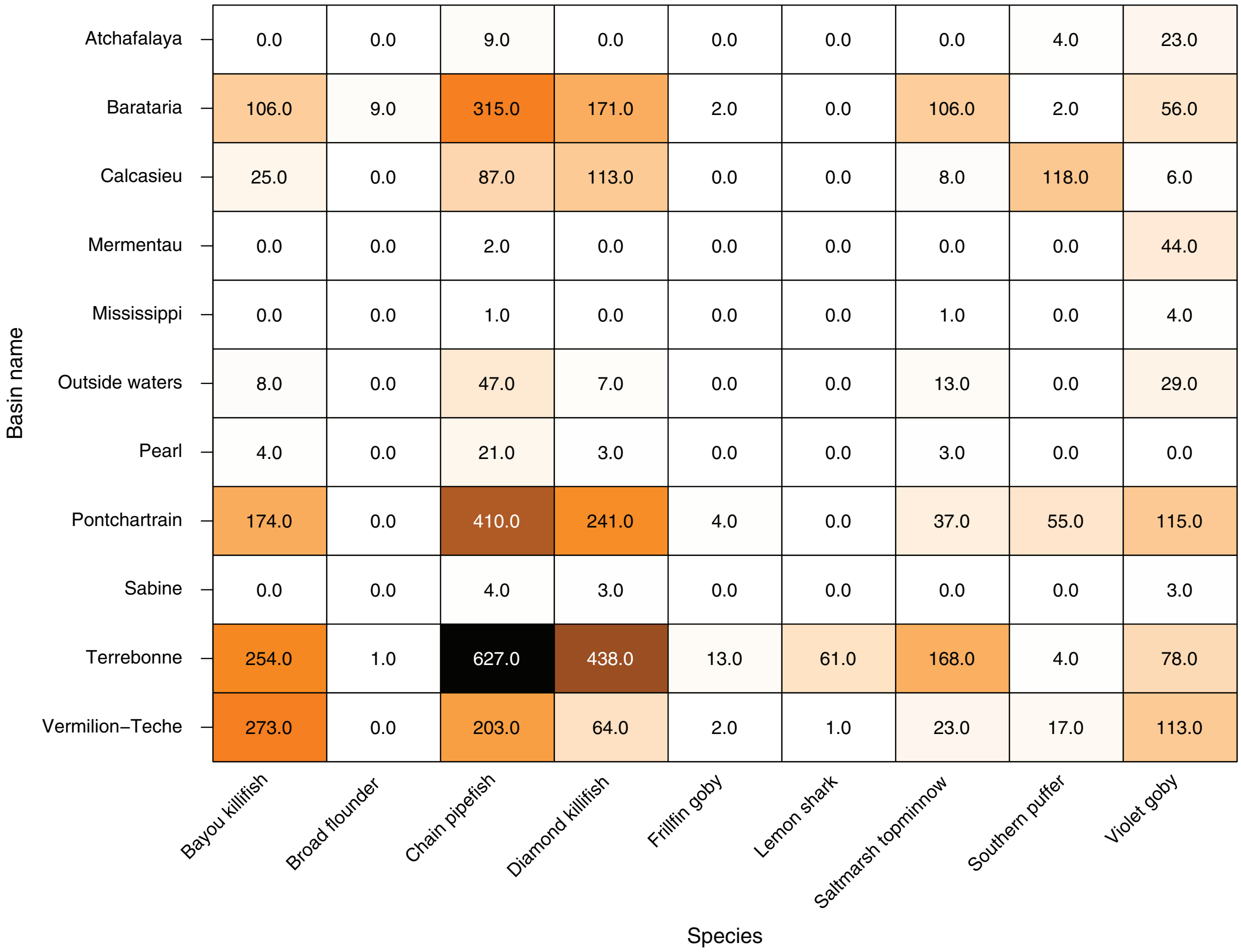


**Fig. 4.** Matrix plot showing combinations of species encounters by location (estuary or coastal area). Numbers in the matrix represent the number of total samples (from 1986 to 2018) encountering a specific SGCN in a specific gear. Cell colours correspond to the numbers; lighter colours indicate fewer samples, and darker colours indicate a larger number of samples.

past century and are expected to continue to change at rates higher than in most other coastal locations. Thus, findings from coastal Louisiana may offer insights into future changes globally, because low-elevation coastal regions, such as the Ganges River delta, Pacific islands, and north-western and south-eastern Europe, may eventually face similar magnitudes of land loss. Although coastal Louisiana fish species have shown less distributional change than might be expected (Cowan *et al.* 2008) given dramatic environmental changes (Couvillion *et al.* 2011), some of this change may not have been reported and could still occur in the future. Much of coastal Louisiana has been altered or exploited by human activities, which has come at a cost to fish habitat (Chesney *et al.* 2000).

In particular, the Mississippi River Delta has experienced extensive changes over the past century that have resulted in a large amount of coastal land loss. To combat land loss, a series of sediment diversions has been proposed that could dramatically alter sediment flows, salinity, water temperature and other core aspects of fish habitat (Elsey-Quirk *et al.* 2019). Sediment diversion discharge scenarios and their salinities could be further evaluated (as in simulations) to better predict how marine SGCN fishes will respond (Das *et al.* 2012). In fact, individual-based modelling of fishes in coastal Louisiana has predicted movements of up to 35 km from diversion sites, along with an increase in individual dispersal (Nyman *et al.* 2013; Rose *et al.* 2014). There is considerable uncertainty regarding predictions of marine fish SGCN population trends in coastal Louisiana. Despite decades of habitat change and stress, many (commercial and recreational) fish species appear resilient (Chesney *et al.* 2000). However, if fish do not move or cannot migrate (e.g. smaller-bodied killifish species), they may also be subjected to suboptimal environmental conditions that could reduce fitness and survival. Moreover, it could be very risky to expect continued resilience in the face of continued habitat changes (Cowan *et al.* 2008; Nyman *et al.* 2013), or to assume that SGCN demonstrate the same resilience that the more commonly monitored species show.

### *Design of future sampling*

Some type of targeted or designed monitoring is recommended for marine fish SGCN. Low occurrence (or detection) of some species may be due to low population size, or it may be from low detection probabilities, and the fishes we called rare may be more common than data would indicate. Furthermore, estuarine

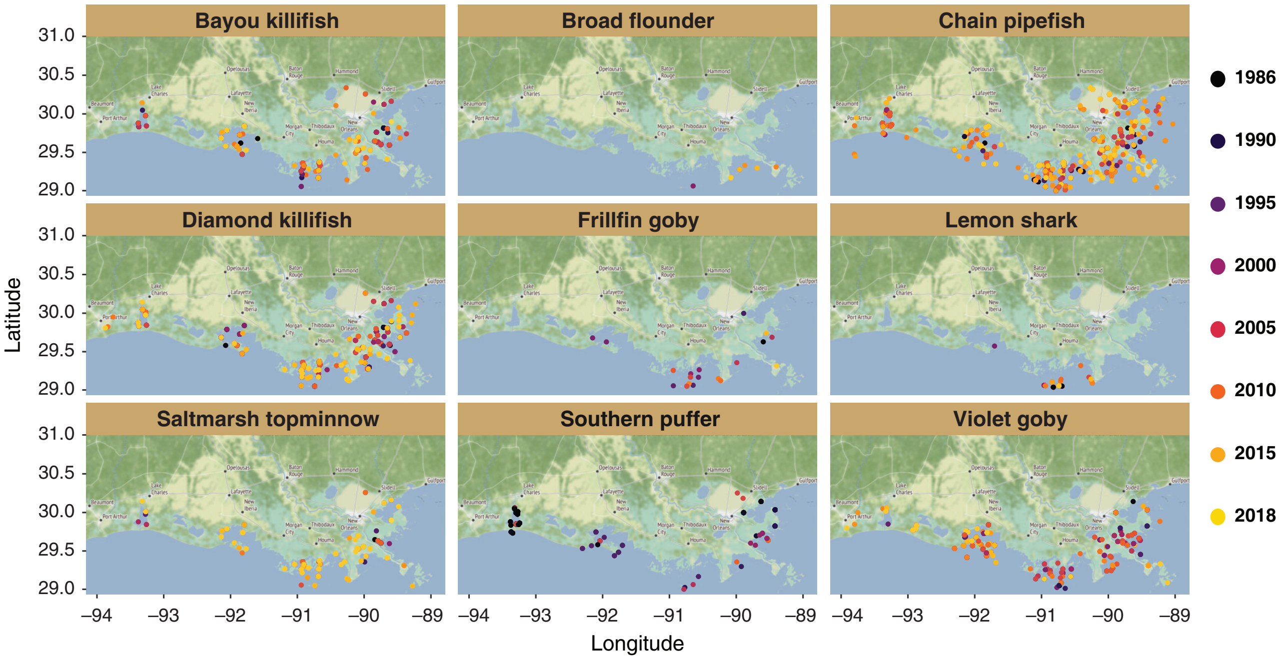


**Fig. 5.** Panel map showing coastal locations of detection for nine of the most common marine fish SGCN. Individual points in a given panel represent a sample that has detected the species. No count or abundance information is included. The detection points are coloured to represent time, with darker colours indicating older samples and lighter colours indicating newer samples. The legend does not include all the colours in the maps but shows the gradient of time and colour with eight example dates.

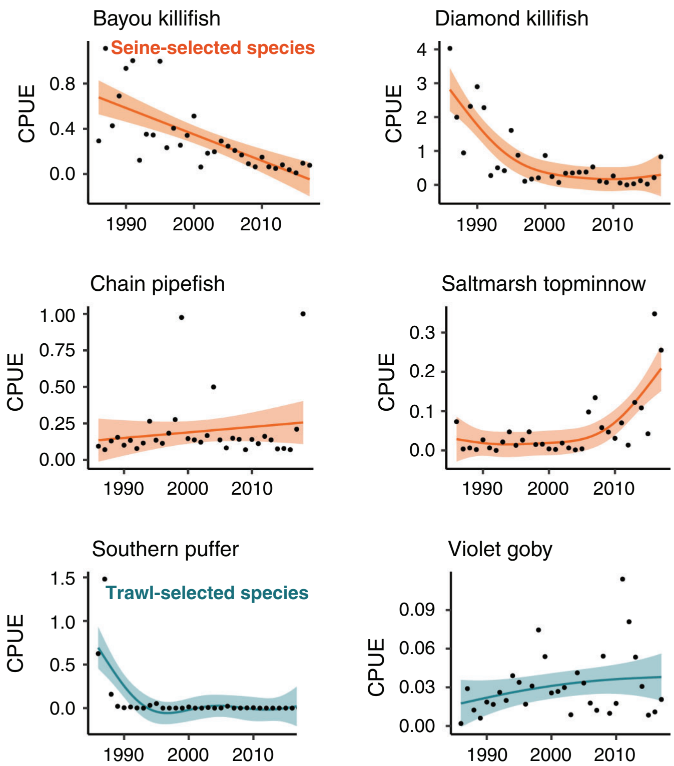


**Fig. 6.** Generalised additive model (GAM) fits (and 95% credible intervals) for the six most encountered marine fish SGCN from 1986 to 2018. Black dots indicate the catch per unit effort (CPUE) data. The GAM estimate is the coloured line, and the credible interval is the shaded region of the same colour. Species displayed in orange indicate seine-selected species, whereas species data displayed in teal indicate a trawl-selected species.

fish species may follow different distributional patterns based on commonness or rarity (Magurran and Henderson 2003). Although many sampling gears are used in the state's monitoring program, gear choice has likely not been based on effective sampling of marine fish SGCN. A greater diversity of gear types and more sampling should result in more captures and thus more inference; however, there are specific sampling design elements that should be considered over simply recommending more sampling. As Nichols and Williams (2006) recommend, surveillance monitoring, although more common, offers poor trend detection and weak inferences, and these sampling weaknesses are further limited by the often-infrequent catches of SGCN. Targeted monitoring of SGCN would provide advantages over surveillance monitoring and likely result in more and stronger information about these under-studied species. Trend detection can also be part of the survey design; recommendations exist on statistical methods, such as Bayesian dynamic linear models, that offer improved trend detection over traditional methods (Wagner *et al.* 2013).

In addition to building on the information presented in this study, such as, for example, species-specific capture relationships for gear, month and location, SGCN fishes could be monitored for abundance or simply presence–absence. Although abundance sampling may provide more information, PA sampling has strong financial benefits (i.e. almost always cheaper), and under certain conditions can outperform abundance sampling for monitoring (Joseph *et al.* 2006). If a species is expected to be recorded >16 times per year, then an abundance survey is recommended; however, infrequently sampled species would likely benefit from a PA sampling design. For Louisiana's marine fish SGCN, several species, such as the killifishes we identified as abundant, could be monitored with the existing FIMP in areas of rapid coastal change (e.g. fragmentation and reduction in marsh edge and submerged aquatic vegetation; Jerabek *et al.* 2017) to monitor and project future population trends given observed changes in marsh habitat. For those common or rare species, a PA survey could be developed on the basis of existing species associations included in this study. Independent of our study, general recommendations and simulation studies can be used to guide fish monitoring nearly anywhere. For instance, in addition to the general points made above about abundance versus PA sampling, program aspects such as sampling frequency, timing and intensity have been simulated so as to make recommendations about designs that are better for measuring species richness, diversity or community sampling (Zhao *et al.* 2017). Xu *et al.* (2015) evaluated sampling in China's Yellow Sea and concluded that a stratified random design had benefits for low-abundance (and aggregated) species, which could have implications for rare and imperilled species.

Along with refinement and development of traditional monitoring programs, fish managers across all habitats should not discount opportunities for other sampling approaches. For instance, environmental DNA (eDNA) is increasingly being used to test for aquatic species and has been used to sample for rare (macroinvertebrate) species (Mächler *et al.* 2014), estuarine fishes (Ahn *et al.* 2020) and marine fishes (Thomsen *et al.* 2012). eDNA holds the promise of efficiency, namely, small amounts of sample (water) could be used to detect a large number of species, and gains in sample efficiency could be invested in broader spatial and temporal coverage. Yet, despite the potential in eDNA, coastal aquatic habitats in Louisiana often exhibit warm temperatures, high turbidity, high biological activity, low dissolved oxygen and frequent water movement, which degrade eDNA fragments and reduce sampling effectiveness (Eichmiller *et al.* 2016; Sassoubre *et al.* 2016) and capture of eDNA that become adsorbed into sediments (Barnes *et al.* 2020). For SGCN fish, eDNA has special promise because it results in potentially less disturbance to fish and habitat (Ahn *et al.* 2020; Jerde 2021), although perhaps at the cost of some lost precision on location (Dressler *et al.* 2020). Given the rarity of these species, degradation or loss of detectable eDNA from an already low concentration would likely be a challenge to implementing current eDNA methods and will require further investigation (e.g. Harrison *et al.* 2019; Barnes *et al.* 2020; Lacoursière-Roussel and Deiner 2021).

Finally, SGCN are often rare, making them of interest to conservation groups. Herein lies some potential for encounter-based citizen science (Bear 2016). Although community-based reporting may be infrequent and non-probabilistic in design, it could be free data and still provide PA inferences across large scales. Regardless of how SGCN sampling may progress in the future, it is likely that many existing sampling programs throughout the world contain unanalysed data on rare species. It is also true that with some development of sampling programs, a much greater volume of data could begin to inform a wide variety of species about which we currently claim to know little.

## Conflicts of interest

The authors declare that they have no conflicts of interest.


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