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Assessing Long-Term Changes to Estuarine Benthic Communities in the Northwestern Gulf of Mexico

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Abstract
The assessment of long-term changes to estuarine biotic community structure is an important first step towards fisheries management and conservation in the face of changes to climate and other extrinsic factors. In Texas, temporal changes in community structure have recently been documented in several independent studies, but such studies are often focused on larger, managed pelagic species, rather than smaller benthic organisms. We used a 38-year (1986–2023) dataset of fishery-independent trawl data to assess spatial and temporal change to estuarine benthic fish and macro-invertebrate communities coast-wide across Texas. We observed significant spatial variability in catch-per-unit-effort (CPUE) that was associated with a known transition from northern (temperate) to southern (sub-tropical) climatic regimes. We also observed significant temporal variability between early (1986–2001) and more recent years (2002–2023), and this variability was associated with changes in overall CPUE, the ratio of pelagic/demersal taxa, Shannon diversity index, taxonomic distinctness, and either positive or negative impacts to annual CPUE of several commonly encountered taxa. Linear regression revealed that changes in community structure (modeled using an ordinated variable from principal components analysis) and community diversity metrics were significantly correlated with both a decline in commercial shrimping effort and an increase in the Atlantic Multidecadal Oscillation (AMO) index. Reduced shrimping effort has reduced bycatch mortality of trawl-associated fish species, many of which have also benefitted from milder winters associated with the warm phase of the AMO. Reduced fishing-related mortality of trawl-associated fish species combined with a warming climate have likely contributed to reorganization of benthic fish and macro-invertebrate communities over time. Our results indicate that climate factors are at least as important as fishing in shaping biotic communities of estuaries in the northwestern Gulf of Mexico, and both factors should be considered when devising management strategies for individual species and estuarine communities alike.

Keywords Atlantic Multidecadal Oscillation · Commercial shrimping · Community structure · Estuary · Gulf of Mexico

Introduction

The Gulf of Mexico (GoM) can be generally described as a transition zone between temperate and sub-tropical climatic and biotic systems (e.g., Stevens et al., 2006). The temperate/sub-tropical gradient is a prominent feature of coastal areas in Texas, where nine major coastal estuaries (Fig. 1) represent a gradient of water temperature and salinity, with these two parameters increasing with decreasing latitude. Lower salinity of the upper coast estuaries is the result of both greater freshwater inflow from major rivers and the region's higher annual rainfall than in southern estuaries (Armstrong, 1987; Kim et al., 2014; Orlando et al., 1991). Rainfall on the Texas coast ranges from 135 to 152 cm year^{-1} in the area around Sabine Lake in the north, to 55 cm year^{-1} on the southern coast in the vicinity of the Upper and Lower Laguna Madre estuaries (Kinard et al., 2021; Texas Water Development Board, 2024). Most of the freshwater inflow for Texas' southern bays is restricted to single major river systems, with highly variable flow. Perhaps one of the most extreme estuarine systems in the world, the Upper Laguna Madre is a hypersaline lagoon that is almost entirely enclosed by land and regularly attains salinity over 60 psu. Freshwater inflow in the Upper Laguna

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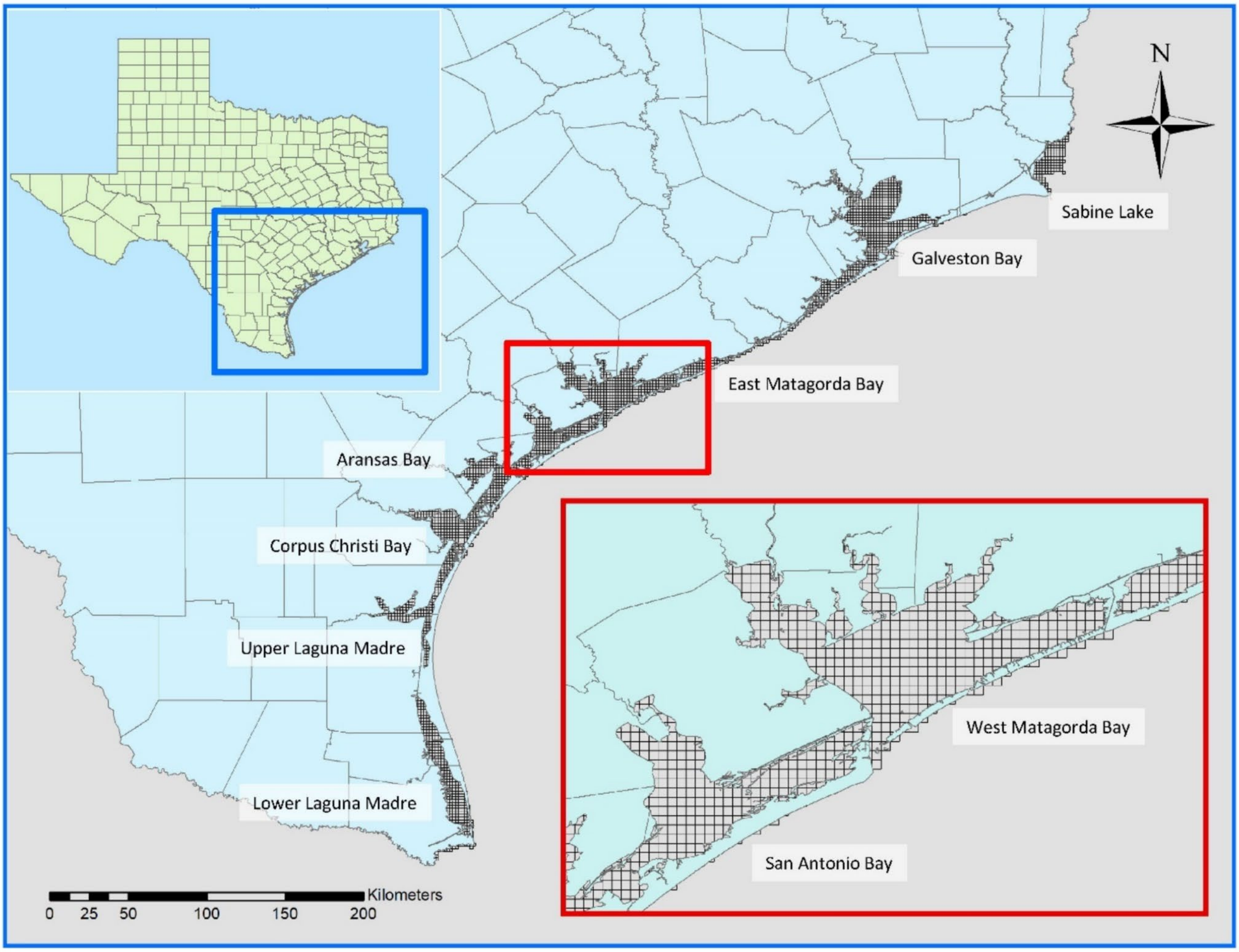

Fig. 1 Map of study area. Cross-hatched regions represent sampling grids for TPWD fishery-independent resource monitoring program

is limited to small, often intermittent, coastal streams, and water exchange with the northwestern GoM is limited to a single channel at its northern end. Texas estuaries are relatively shallow, with average depths varying from 1 m in the Upper and Lower Laguna Madre and East Matagorda Bay to about 2 m in other bays, although areas around dredged navigation channels may be ≥ 12 m deep (Armstrong, 1987; Orlando et al., 1991; Cifuentes & Kaldy, 2006). Dynamic climatic and hydrological variation shapes the estuarine biotic communities in these systems, thus making coastal Texas an excellent laboratory for exploring the effects of climatic variation on the community structure of fish and aquatic invertebrates.

The Coastal Fisheries Division of the Texas Parks and Wildlife Department (TPWD) has conducted regular monthly sampling in Texas' coastal estuaries using bag seines, gill nets, and trawls as part of a fishery-independent resource monitoring program since 1982. These long-term datasets provide opportunities to assess the spatial and temporal trends in species abundance and community structure in Texas estuaries; and several recent studies have begun to address this goal. Coffey et al. (2025) used TPWD trawl data to examine how salinity affected the community structure of nekton within and among Texas estuaries and how this varied among wet and dry periods from 1982 to 2020. Bag seine and gill net data collected by TPWD have been previously used to examine changes in abundance and diversity of fishes and invertebrates along the Texas coast in relation to climatic variation from the 1980s to early twenty-first century (Ceron et al., 2023; Fujiwara et al., 2019, 2022; Pawluk et al., 2022; Sluis et al., 2025). Fujiwara et al. (2022) noted that winter-spawning species underwent a general decline in abundance from 1982 to 2019, whereas species that spawn outside of winter had become more common. Fujiwara et al. (2019), Pawluk et al. (2022), and Ceron et al. (2023) noted that tropical species had increased in abundance since the 1980s as well as increases in species richness and diversity. Fujiwara et al. (2019) and other studies (Ceron et al., 2023; Fujiwara et al., 2022; Pawluk et al., 2022) concluded that most of the observed changes in abundance, diversity, and structure among littoral fish and macro-invertebrate communities were driven by a warming climate and generally milder winters.

Of the gears employed in the TPWD fishery-independent monitoring program, bottom trawls are the most effective for sampling taxonomic and community structure of benthic habitats, and it is also the only gear in the TPWD portfolio that is used in open-water sampling grids (i.e., it is not deployed solely along shorelines). Despite this, community assessments from the bottom trawl sampling program in Texas are generally less well-represented in the community change literature than either gill net (Ceron et al., 2023; Pawluk et al., 2022; Sluis et al., 2025) or bag seine (Fujiwara et al., 2019, 2022) datasets (although see Coffey et al., 2025). Bottom trawl datasets have previously been recognized for their importance globally in assessing marine species climate-driven range shifts, and especially for assessing species vulnerabilities and adaptive management in the face of changing climate (Gervelis et al., 2023; Maureaud et al., 2021).

In this study, we used the long-term fishery-independent trawl dataset maintained by TPWD to examine how fish and macro-invertebrate communities of Texas estuaries are structured geographically and how the coastwide demersal estuarine community has changed from 1986 to 2023. Furthermore, we evaluated the multivariate nature of biotic change in the context of long-term temporal changes in fishing behaviors (shrimp trawling and oyster dredging) and climatic oscillations. Our specific objectives were the following: (1) describe and assess the overall structure of fish and macro-invertebrate communities in Texas inshore waters using fishery-independent trawl gear that is similar to trawls deployed by the commercial shrimping industry; (2) examine the spatial and temporal trends in abundance of the most common species; and (3) infer possible causes of observed changes, particularly in relation to anthropogenic factors (fishing) and climatic factors. The size and scope of these data allow for broad-scale analysis of climate- and fishing-induced changes to estuarine communities in Texas, and the interpretations of the drivers of change could be broadly extrapolated to make inferences about similar community shifts observed in other GoM estuaries.

Methods

Field Techniques

The Coastal Fisheries Division of TPWD has conducted regular monthly sampling using trawls as part of a fishery-independent resource monitoring program in seven major estuaries of the Texas coast since 1982. Sampling of Sabine Lake began in 1986 and East Matagorda Bay in 1987. We limited our data to sampling collected between 1986 and 2023 due to the potential impact of large changes in sampling effort prior to 1986. The 1986–2023 dataset encompassed 66,458 individual sample deployments ($\bar{x}$ samples/year = 1749, Table 1). Trawl samples were conducted between 0.5 h before sunrise and 0.5 h after sunset, with half of the scheduled monthly trawls samples collected during the first 15 days and the remainder collected during the remaining days of the month (Martinez-Andrade, 2015). Twenty trawls per month were performed in larger estuaries (Sabine Lake, Galveston, West Matagorda, San Antonio, Aransas, and Corpus Christi Bays), whereas ten trawls per month were performed in East Matagorda Bay and the Upper and Lower Laguna Madre. Coastal Fisheries trawls were 6.1-m wide otter

Table 1 Hydrological and physical characteristics of the Texas Gulf of Mexico estuaries

Characteristic	SL	GB	EMB	WMB	SAB	AB	CCB	ULM	LLM
Temp. (°C)	21.7 ± 0.09	22.0 ± 0.07	22.8 ± 0.10	22.4 ± 0.07	22.7 ± 0.07	22.6 ± 0.07	22.9 ± 0.06	23.5 ± 0.09	23.8 ± 0.08
Salinity (ppt)	7.3 ± 0.08	15.9 ± 0.09	24.0 ± 0.10	23.4 ± 0.08	18.3 ± 0.11	21.1 ± 0.09	31.2 ± 0.06	38.2 ± 0.15	33.3 ± 0.08
Turbidity (ntu)	20.0 ± 0.34	23.7 ± 0.40	32.9 ± 0.79	22.3 ± 0.39	23.6 ± 0.38	18.6 ± 0.39	13.6 ± 0.19	21.6 ± 0.55	20.7 ± 0.69
DO (mg/L)	7.9 ± 0.02	7.7 ± 0.02	7.4 ± 0.02	7.5 ± 0.02	7.8 ± 0.20	7.5 ± 0.02	7.0 ± 0.02	6.8 ± 0.03	7.2 ± 0.03
Mean depth (m)	2.2 ± 0.02	2.4 ± 0.01	1.8 ± 0.01	2.9 ± 0.01	2.0 ± 0.01	2.5 ± 0.01	3.6 ± 0.01	2.1 ± 0.01	2.0 ± 0.01
Maximum depth (m)	15.3	14.6	7.0	20.0	16.8	11.2	17.4	6.1	14.2
SA (ha × 1000)	18.3	139.7	15.3	98.9	57.9	45.2	43.3	41.0	72.7
FI (km^3)	17.3	13.6	0.7	4.3	3.1	0.6	0.7	0.3	0.7
N	5308	9368	4678	9368	9367	9358	9356	4828	4678

Mean (± SE) values of water temperature (temp.), salinity, turbidity, and dissolved oxygen (DO), and depth (m), maximum depth, and number of trawls (*N*) performed over the study period are based on data collected by TPWD Coastal Fisheries Division as part of trawl sampling from 1986–2023. Surface area (SA) and freshwater inflow (FI) are derived from the Texas Water Development Board (2024) and Matlock & Osborn (1982). Codes for bays are as follows: *SL*, Sabine Lake; *GB*, Galveston Bay; *EMB*, East Matagorda Bay; *WMB*, West Matagorda Bay; *SAB*, San Antonio Bay; *AB*, Aransas Bay; *CCB*, Corpus Christi Bay; *ULM*, Upper Laguna Madre; and *LLM*, Lower Laguna Madre trawls with 38 mm stretched nylon multifilament mesh throughout. Trawl doors were 1.2 m long and 0.5 m wide and constructed of 13 mm plywood with angle iron framework and iron runners. This construction was qualitatively similar to the design of trawls used in the inshore commercial shrimp trawl fishery in Texas.

Each estuary was divided into 1-min^2 grids aligned with the geographic coordinate system, and grids are sampled in stratified random design. A grid was considered sampleable by trawl if one-third of that grid's depth at mean low tide is ≥ 1 m. Galveston, West Matagorda, San Antonio, Aransas, and Corpus Christi Bays are stratified into equal-sized upper and lower bay zones with half of the monthly trawl samples collected in the upper zone and half in the lower zone to ensure good spatial distribution of samples. The smaller estuaries (Sabine Lake, East Matagorda Bay, and Upper and Lower Laguna Madre) were not spatially stratified. Trawls were never conducted in the same grid more than once per month. Trawl samples were also not collected from navigation channels.

Salinity (ppt), water temperature (C°), dissolved oxygen (mg/L), and turbidity (ntu) were collected 0.3 m off the bottom before trawling began. Depth was measured to nearest 0.1 m using a marked PVC pole or an on-board depth finder. Trawls were towed at 4.8 kph for 10 min (0.167 h) in a circular manner near the center of each grid. Latitude and longitude were recorded before and after the completion of the trawl. Organisms captured by the trawl were identified to species-level whenever possible. Marsh and daggerblade grass shrimps (*Palaemon vulgaris* and *P. pugio*) were identified to the level of genus because of the large numbers of grass shrimps collected and the difficulty of using morphological traits to separate these two species in the field. Species such as silversides (*Menidia* spp.), bonefishes (*Albula* spp.), and ladyfishes (*Elops* spp.) were also identified only to genus level because congeners can only be reliably separated using genetic methods (McBride et al., 2010; Olsen et al., 2016; Picket et al., 2020; Williford et al., 2022). Organisms identified to genus-level were treated as species in later analyses. All individuals were counted. Catch per unit effort (CPUE) per sample for each species was calculated as the number of individuals captured divided by the length of time, in hours, for which the trawl was pulled. For each sample, the first 19 individuals of each species (except for hermit crabs) were measured. Length was measured (in mm) as follows: fish from the tip of snout to tip of longest caudal fin ray, shrimp were from the tip of rostrum to tip of telson, squid from posterior mantle margin to top of pen, brachyuran crabs as lateral spine width, bivalves as the widest portion of shell, snails the longest axis of shell, and sea stars as the maximum diameter (i.e., maximum arm span).

Statistical Analysis

A relatively small number of species made up the bulk of the organisms collected through trawls (see Results); therefore, we focused our analysis on the 40 most abundant species. The spatial and temporal dynamics of the most common taxa will likely reflect the major changes in community composition (Collie et al., 2008). We calculated overall and annual catch (number of individuals), CPUE, and mean length (mm) of each focal species, and classified each focal species as pelagic or demersal (including those that are usually classified as benthic or benthopelagic) using information obtained from either FishBase (Froese & Pauly, 2024) or SeaLifeBase (Palomares & Pauly, 2024). To assess whether the sampling methods and effort employed by TPWD Coastal Fisheries was sufficient to detect spatial differences among the nine bays, we performed a redundancy analysis (RDA, Legendre & Legendre, 1998) using $\log_{10}$-transformed $(x + 1)$ bay-specific annual CPUE data. The ordination axes of RDA are linear combinations of independent (explanatory) variables. Yearly averages of water temperature, salinity, dissolved oxygen, depth, and turbidity were used as explanatory variables. Results were illustrated as a biplot using type 1 scaling (Legendre & Legendre, 1998). We further assessed differences among the bays by calculating the overall catch of each species in each bay. The RDA was carried out using the computer program PAST, version 4.13 (Hammer et al., 2001).

We examined coastwide temporal trends at the species and community levels using multiple approaches. First, we explored temporal trends of the forty focal species by regressing each species' $\log_{10}$-transformed $(x + 1)$ annual coastwide CPUE against time (years). For community level analysis, we initially assessed differences among years by performing a hierarchical cluster analysis based on Bray–Curtis dissimilarity (Bray & Curtis, 1957) using $\log_{10}$-transformed $(x + 1)$ CPUE. The results of this analysis suggested that the time span consisted of two clusters: one consisting of years 1986–2001 and another composed to the remaining years 2002–2023 (although the year 2000 fell in with the later cluster; Fig. 2). For all subsequent analyses, we referred to 1986–2001 as the early period and 2002–2023 as the late period. To determine whether significant differences existed between suites of organisms observed between the early and late periods, we performed a one-way analysis of similarities (ANOSIM; Clarke, 1993). We further assessed differences amongst the two time periods by conducting similarity of percentages (SIMPER; Clarke, 1993). SIMPER determines how much each species contributes to the dissimilarity between groups. Bray–Curtis dissimilarity index was applied to $\log_{10}$-transformed $(x + 1)$ CPUE data for both the ANOSIM and SIMPER analyses.

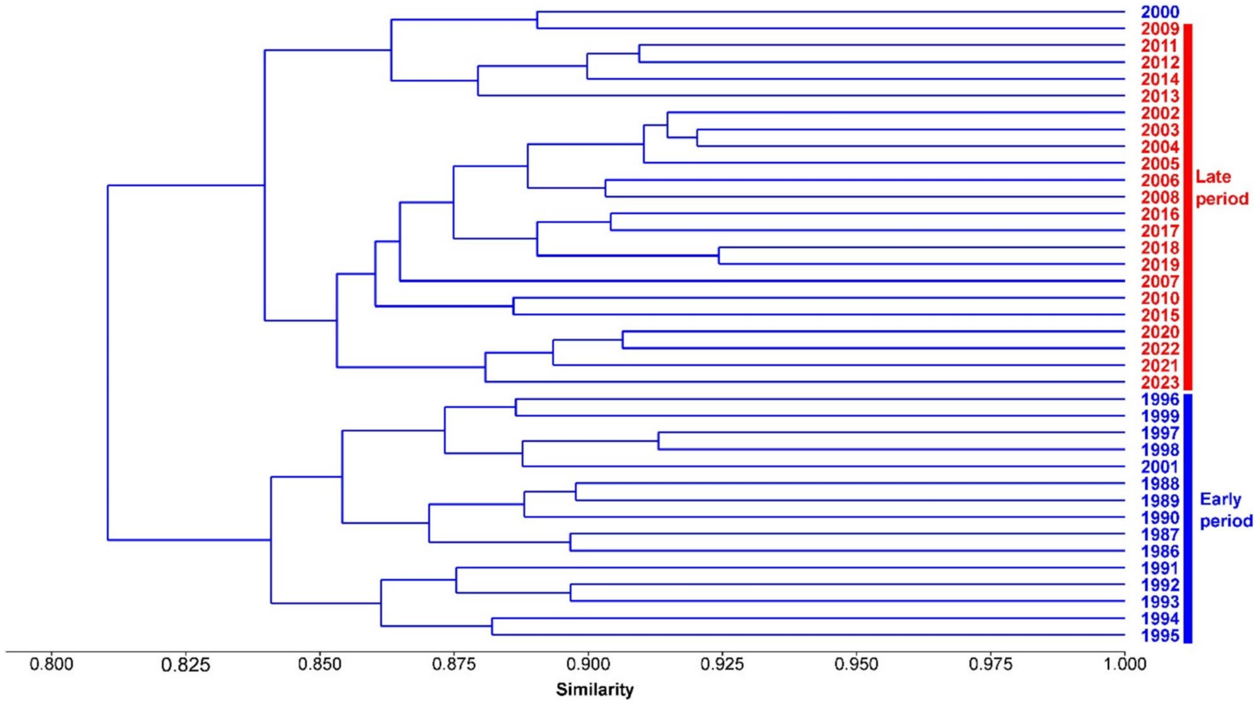

Fig. 2 Dendrogram of years (1986–2023) based on CPUE data of 40 most abundant species captured TPWD fishery-independent trawls from Texas inshore waters and inferred using Bray–Curtis dissimilarity distance. Note the existence of two clusters representing early (1986–2001) and late (2002–2023) periods

We visualized how the estuarine biotic community had changed between 1986 and 2023 by performing a principal components analysis (PCA) using the species as explanatory variables. PCA creates new variables (components) that are ordinated combinations of raw variables and that account for as much variation in the data as possible. The relative loadings of species $\log_{10}$-transformed $(x+1)$ CPUE on ordinated PCA variables allowed another way to determine which species were driving most of the community change from 1986 to 2023. The clustering analysis, ANOSIM, SIMPER, and PCA were performed using PAST. We also constructed plots of the annual coastwide CPUE for species that contributed the most to the differentiation of the two time periods as inferred by either PCA or SIMPER as well as for commercially important penaeid shrimps. Finally, we regressed annual mean length data for each species against time to assess whether changes in body size were correlated with changes in CPUE.

Lastly, we calculated six annual metrics as additional assessments of community-level changes over time. We used annual CPUE of each focal species to compute two biodiversity estimates, Shannon (1948) diversity index and taxonomic distinctness (Clarke & Warwick, 1998; Warwick & Clarke, 1995), using the software program PAST. The Shannon diversity index quantifies the proportion of individuals per species in a dataset, and the index should decline with decreasing representation among taxa. Taxonomic distinctness accounts for the distance between as well as CPUE among differing taxonomic levels and is expected to decrease with increasing disturbance (Rogers et al., 1999; Warwick & Clarke, 1995, 1998). To calculate taxonomic distance, we used six taxonomic levels: species, genus, family, order, class, and phylum (Appendix S1). Taxonomy of fishes was based on Near and Thacker (2024) and taxonomy of macro-invertebrates was derived from the World Register of Marine Species (WoRMS Editorial Board, 2024).

Total annual CPUE was computed by summing the entire catch of the 40 focal species by year and dividing by the total trawling hours. Annual pelagic-demersal ratio was calculated as the number of individuals classified as pelagic divided by number of individuals of demersal species (Collie et al., 2008; de Leiva Moreno et al., 2000). The invertebrate-fish ratio was calculated in a similar manner: the number of invertebrates divided by the number of fish for each year. We were unable to compute biomass because weight data was not collected; therefore, we used length data to calculate mean community length (Collie et al., 2008) as a proxy. We multiplied the overall mean length of each focal species by the species' annual CPUE and the subsequent products were divided by the total CPUE of relevant year. Simple linear regression was used to determine whether any of the six community metrics exhibited significant temporal trends.

We sought to infer the impacts of climate and commercial fishing on community structure by assessing the relationship between dependent variables, the first principal component (PC1) and community metrics (total annual CPUE, Shannon diversity index, taxonomic distinctness, community mean size, invertebrate-fish ratio, and pelagic-demersal ratio), and four predictor variables: (1) number of commercial bait trawling licenses issued by TPWD; (2) coastwide commercial oyster harvest in Texas; (3) the Atlantic Multidecadal Oscillation (AMO); and (4) the Pacific Decadal Oscillation (PDO). Annual harvest of oysters in metric tons was obtained from the Fisheries One Stop Shop of the National Oceanic and Atmospheric Administration (NOAA, https://www.fisheries.noaa.gov/foss). The AMO is an ongoing, long-duration driver of sea surface temperature, with cool and warm phases that each last 20–40 years (Endfield et al., 2001; McCabe et al., 2004), is a major driver of sea surface temperature change in the North Atlantic and the GoM (del Monte-Luna et al., 2015; Drinkwater et al., 2014; Muller-Karger et al., 2015), and influences long-term trends in precipitation across North America (Curtis, 2008; Feng et al., 2010; McCabe et al., 2004). The PDO is another long-term climatic phenomenon that affects the GoM. The PDO has been described as a long-lived El Niño-like pattern in the Pacific Ocean, with distinct warm and cold phases (Mantua & Hare, 2002; Zhang et al., 1997). The simultaneous occurrence of the PDO cold phase and the AMO warm phase increases the intensity of drought conditions in Mexico and southwestern United States, conversely the warm phase of the PDO combined with the cool phase of the AMO can increase river discharge into the northern GoM due enhanced precipitation (Clark et al., 2014; Endfield et al., 2001; Murgulet et al., 2017; Pavia et al., 2006). The AMO index is based on the average of sea surface temperature in the North Atlantic between 0° and 60° N, and the PDO index is based on the average of sea surface temperatures of the North Pacific poleward of 20°N. Monthly values of the AMO index were obtained from obtained from NOAA's National Centers for Environmental Information (https://www1.ncdc.noaa.gov/pub/data/cmb/ersst/v5/index/ersst.v5.amo.dat) and monthly values of the PDO were obtained from the NOAA's Physical Sciences Laboratory (https://psl.noaa.gov/pdo/). Yearly means of the AMO were derived by averaging the monthly (Jan-Dec) values. Temporal trends of the four predictor variables were examined and compared to trends observed in the community metrics. The nature and strength of the relationship between each predictor and each dependent variable (PC1 and community metrics) was assessed using simple linear regression.

Results

The 40 most abundant species consisted of 25 species of ray-finned fishes and 15 species of macro-invertebrates, including ten crustaceans, four mollusks, and one echinoderm (Table 2). These 40 species accounted for 97% ($n = 5{,}337{,}939$) of the 5,518,715 organisms captured between 1986 and 2023. Most of the focal species were classified as demersal, with only five pelagic species present among the focal group: Bay Anchovy (*Anchoa mitchilli*), Gulf Menhaden (*Brevoortia patronus*), Atlantic Spadefish (*Chaetodipterus faber*), Atlantic Bumper (*Chloroscombrus chrysurus*), and Threadfin Shad (*Dorosoma petenense*). Overall, Atlantic Croaker (*Micropogonias undulatus*), Pinfish (*Lagodon rhomboides*), Spot (*Leiostomus xanthurus*), and Bay Anchovy were the four most abundant fishes. Brown shrimp (*Penaeus aztecus*), white shrimp, Atlantic brief squid (*Lolliguncula brevis*), and blue crab (*Callinectes sapidus*) were the most abundant macro-invertebrates. The species comprising the greatest proportion of the annual catch each year alternated among Spot, Pinfish, and Atlantic Croaker. Spot was the most abundant species in 11 years of the study period (1988, 1990, 1996, 1998, 2001, 2003, 2007, 2012, 2014, 2018, 2019, 2021), Pinfish was the most abundant species in 12 years of the study (1989, 1999, 2000, 2002, 2004, 2006, 2008, 2009, 2011, 2013, 2020, 2022), and Atlantic Croaker was numerically dominant other years (1986, 1987, 1991–1995, 1997, 2005, 2010, 2015–2017, 2023). Brown shrimp was the most abundant macro-invertebrate in 23 of 38 years of the study period (1986–1996, 2000, 2001, 2006, 2009–2015, 2021, and 2023), whereas in other years white shrimp was the most abundant macro-invertebrate.

RDA based on CPUE (Fig. 3) and raw catch data (number of individuals, Table 3) revealed substantial spatial structuring along the Texas coast. Axis 1 and 2 of the first RDA explained a combined 27% of the variance in the dataset. The first gradient (axis 1) was driven primarily by salinity and temperature, with samples from the Upper and Lower Laguna Madre forming a cluster of points distinct from those of other bays (Fig. 3 and Table S1). The second gradient (axis 2) was primarily governed by depth, with Corpus Christi Bay clustering separately from shallower bays. Atlantic Croaker, Sand Seatrout (*Cynoscion arenarius*), Gulf Menhaden, white shrimp, and Atlantic rangia (*Rangia cuneata*) were negatively correlated with temperature and salinity and more closely associated with upper coast bays (Sabine Lake, Galveston Bay, and East Matagorda Bay). In contrast, Pinfish, pink shrimp (*Penaeus duorarum*), Pigfish (*Orthopristis chrysoptera*), Silver Perch (*Bairdiella chrysoura*), and Gulf grassflat crab (*Dyspanopeus texanus*) were more closely associated

Table 2 Top 40 species captured in TPWD fishery-independent trawls between 1986–2023

Species	Habitat	*N*	Freq	Mean TL	TL (min–max)
Anchoa mitchilli	Pelagic	307,332	42	50.5 ± 0.03	5–110
Ariopsis felis	Demersal	111,379	37	195.1 ± 0.24	20–762
Bagre marinus	Demersal	83,388	15	142.3 ± 0.19	10–765
Bairdiella chrysoura	Demersal	145,121	30	129.3 ± 0.09	10–303
Brevoortia patronus	Pelagic	172,403	27	96.6 ± 0.12	8–341
Callinectes sapidus	Demersal	132,513	38	79.5 ± 0.13	6–286
Callinectes similis	Demersal	48,009	14	46.4 ± 37	5–125
Chaetodipterus faber	Pelagic	7357	5	89.2 ± 0.41	3–328
Chloroscombrus chrysurus	Pelagic	54,947	6	85.6 ± 0.16	16–234
Citharichthys spilopterus	Demersal	8121	7	93.8 ± 0.22	8–198
Cynoscion arenarius	Demersal	57,076	21	123.6 ± 0.21	7–443
Cynoscion nothus	Demersal	8851	3	110.8 ± 0.40	21–333
Dorosoma petenense	Pelagic	12,226	6	124.2 ± 0.24	11–322
Dyspanopeus texanus	Demersal	35,931	5	13.9 ± 0.04	3–38
Ictalurus furcatus	Demersal	19,684	2	203.6 ± 0.76	26–748
Lagodon rhomboides	Demersal	823,640	44	112.4 ± 0.04	9–442
Leiostomus xanthurus	Demersal	814,923	54	126.3 ± 0.05	3–361
Lolliguncula brevis	Demersal	369,330	36	49.1 ± 0.04	3–120
Luidia clathrata	Demersal	16,618	2	113.1 ± 0.39	17–226
Micropogonias undulatus	Demersal	940,007	63	116.8 ± 0.06	8–602
Mugil cephalus	Demersal	28,177	8	203.7 ± 0.47	12–642
Opsanus beta	Demersal	7528	3	141.3 ± 0.80	5–381
Orthopristis chrysoptera	Demersal	21,825	7	131.4 ± 0.29	5–382
Pagurus pollicaris[1]	Demersal	8312	6	31	na
Palaemon spp.	Demersal	33,521	3	29.1 ± 0.01	2–70
Penaeus aztecus	Demersal	484,356	36	96.3 ± 0.05	6–221
Penaeus duorarum	Demersal	43,378	11	90.7 ± 0.10	8–198
Penaeus setiferus	Demersal	359,729	37	84.7 ± 0.04	6–218
Peprilus burti	Demersal	22,038	9	84.9 ± 0.18	15–235
Pogonias cromis	Demersal	14,173	7	254.1 ± 1.14	14–1436
Polydactylus octonemus	Demersal	8978	4	157.2 ± 0.29	15–299
Rangia cuneata	Demersal	59,341	3	31.4 ± 0.08	6–98
Rangia flexuosa	Demersal	13,131	1	33.2 ± 0.19	7–84
Selene setapinnis	Demersal	10,215	4	85.4 ± 0.26	9–466
Solenosteira cancellaria	Demersal	9263	3	27.2 ± 0.07	5–332
Sphoeroides parvus	Demersal	10,802	7	70.4 ± 0.22	6–150
Squilla empusa	Demersal	7319	5	88.8 ± 0.26	8–216
Stellifer lanceolatus	Demersal	7162	3	87.1 ± 0.42	17–195
Tozeuma carolinense	Demersal	7071	1	35.3 ± 0.14	4–74
Trichiurus lepturus	Demersal	12,764	8	352.3 ± 0.95	24–982

For each species we provide the habitat classification (demersal or pelagic), number of individuals captured during the study period (*N*), frequency of occurrence (Freq.), and the mean, minimum, and maximum of total length (TL, mm) of each species measured

[1]Carapace length of *Pagurus pollicaris* was obtained from Gosner (1978). TPWD does not measure hermit crabs as part of its resource monitoring program

with Upper and Laguna Madre and their abundances were positively correlated with temperature and salinity. Gulf Butterfish, Spot, Atlantic Bumper, Atlantic brief squid, and lesser blue crab (*Callinectes similis*) were positively correlated with depth and were more associated with deeper bays (West Matagorda, San Antonio, Aransas, and Corpus Christi Bays).

Raw catch data paralleled the results from the RDA. Atlantic Croaker, Sand Seatrout, Gulf Menhaden, and white shrimp exhibited north-to-south decline in the number of

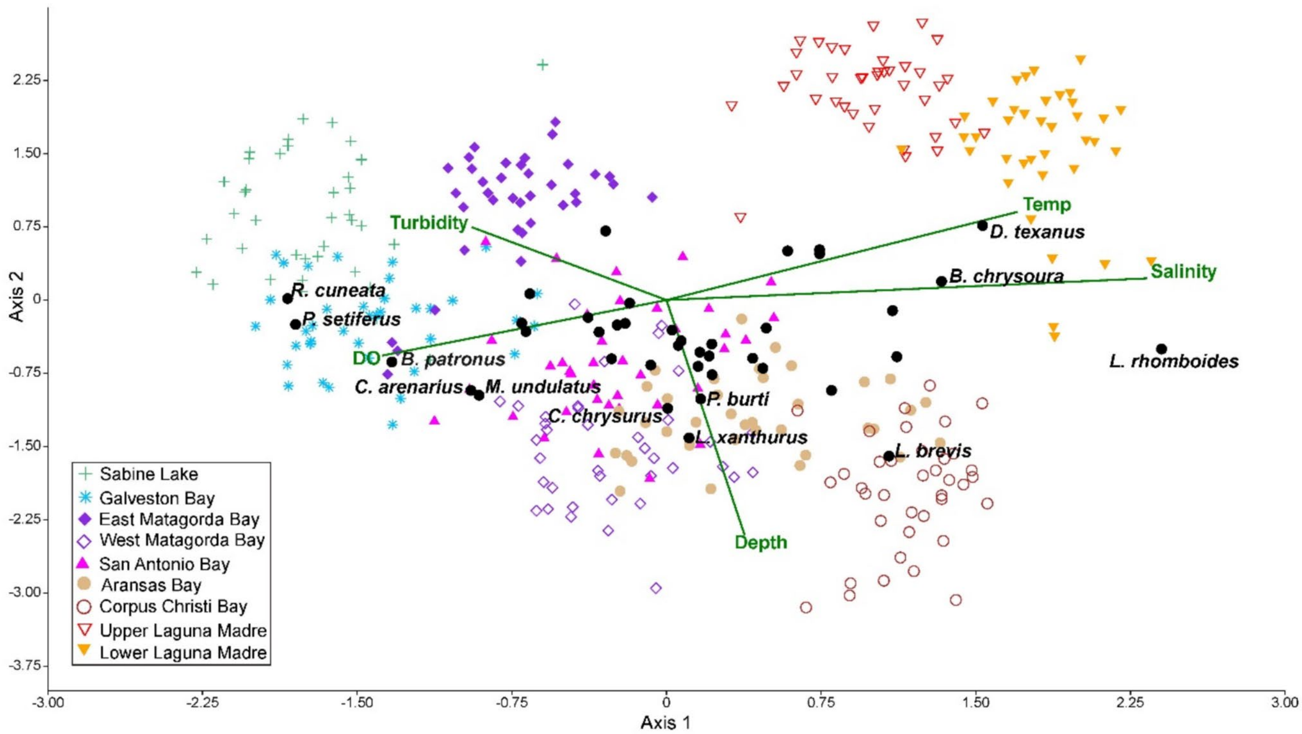

Fig. 3 Ordination of results from RDA of organismal sample frequency data from fishery-independent trawling in Texas inshore waters from 1986 to 2023 illustrating the sensitivity of sampling protocol used in TPWD in its resource monitoring program. RDA is an ordination technique in which ordination is constrained by additional variables, in this case water quality variables collected alongside each trawl deployment used in this study. Green vector arrows represent environmental predictors and are labeled with the name of the corresponding explanatory variable. Species are indicated by black dots. To enhance clarity, only the species with the largest axis scores (≥ 0.25) are labeled

individuals caught, whereas opposite trends were observed among Pinfish, Pigfish, Silver Perch, pink shrimp, and Gulf grassflat crab. Freshwater and oligohaline species, such as Blue Catfish (*Ictalurus furcatus*), Threadfin Shad, Atlantic rangia, and brown rangia (*Rangia flexuosa*), were more abundant in river-dominated bays of Sabine Lake and Galveston and San Antonio Bays. The catches of most species were lower in the hypersaline Upper Laguna Madre. Grass shrimp (*Palaemon* spp.), arrow shrimp (*Tozeuma carolinense*), and Black Drum (*Pogonias cromis*) were exceptions to this general trend and the largest catches of these three species occurred in the Upper Laguna Madre. The largest catches of Gulf grassflat crab occurred in the Lower and Upper Laguna Madre. Overall, the position of samples from each bay system on the RDA plot demonstrated that the sampling method and effort provides sufficient data sensitivity to detect the expected biotic and hydrological differences between the nine major bays on the Texas coast.

Twelve species (seven macro-invertebrates and five fishes) exhibited significant negative trends in annual CPUE from 1986 to 2023, whereas the CPUE of 14 species (three macro-invertebrates and 11 fishes) increased during the same timeframe (Fig. 4). Based on the slope of the regression (m), the sharpest declines in annual CPUE were observed among blue crab, Atlantic rangia, and lesser blue crab, whereas Gafftopsail Catfish (*Bagre marinus*) and Bay Anchovy exhibited the largest increases in annual CPUE. The ANOSIM indicated that significant differences existed in the faunal composition of the early and late periods ($R = 0.718$, $P < 0.001$). The SIMPER results showed that 24 of the 40 species included in the analysis were responsible for 75% of the differentiation between the two time periods. Taxa providing the largest individual contributions to differentiation between the early and late periods, included Atlantic rangia (*Rangia cuneata*, 5.6%), blue crab (5.2%), Gafftopsail Catfish (5.2%), lesser blue crab (4.6%), and Atlantic bumper (3.8%).

The PCA biplot showed a clear distinction between the early and late periods (Fig. 5), which corroborated results from ANOSIM and SIMPER. Principal components (PC) 1 and 2 accounted for 43% of the variance. Years 1986–2001 had negative loadings on PC1 and the remaining 22 years had positive loadings on PC1 (Table S2). Twelve taxa with negative loadings on PC1 also exhibited significant declines in annual CPUE. Thirteen species that had loadings of $\geq |0.2|$ on PC1 were responsible for most of the

Table 3 Total catch (number of individuals) of the top 40 species captured by TPWD fishery-independent trawls from each bay and coastwide between 1986–2023

Species	SL	GB	EMB	WMB	SAB	AB	CCB	ULM	LLM
Anchoa mitchilli	26,737	23,900	11,104	41,457	35,543	55,969	78,910	21,899	11,813
Ariopsis felis	5328	8182	5976	14,732	16,367	20,485	32,735	2568	5006
Bagre marinus	1546	5823	3832	15,720	28,140	20,772	6799	590	166
Bairdiella chrysoura	697	4250	7754	7706	25,578	48,503	23,726	6923	19,984
Brevoortia patronus	11,992	40,029	6152	26,059	45,607	27,618	12,730	1966	578
Callinectes sapidus	6835	14,905	8459	11,456	38,825	27,674	7346	6718	10,295
Callinectes similis	59	2263	490	5469	5615	10,453	20,244	695	2721
Chaetodipterus faber	1122	1537	798	1330	538	615	1149	36	232
Chloroscombrus chrysurus	846	9345	204	26,546	2257	2155	13,285	6	303
Citharichthys spilopterus	590	1023	429	1588	1898	1350	927	115	201
Cynoscion arenarius	7403	13,699	4948	9419	2575	6927	10,947	99	1059
Cynoscion nothus	105	453	13	5833	881	138	1282	6	140
Dorosoma petenense	1286	5775	134	2027	385	2078	531	6	4
Dyspanopeus texanus	29	7	0	2	1	1843	1656	15,149	17,244
Ictalurus furcatus	1967	5617	1	925	10,738	53	383	0	0
Lagodon rhomboides	6164	6701	3342	23,559	72,963	141,409	433,197	46,780	89,525
Leiostomus xanthurus	28,778	43,229	7707	116,141	110,446	238,566	238,013	18,036	14,007
Lolliguncula brevis	431	13,116	3618	53,395	17,825	27,674	62,524	2122	3960
Luidia clathrata	0	0	0	5327	12	79	2141	4	9055
Micropogonias undulatus	68,553	189,348	30,885	166,827	159,096	169,621	124,496	10,697	20,156
Mugil cephalus	3876	5779	2028	804	3393	6912	3808	1303	274
Opsanus beta	9	90	44	47	141	545	124	1598	4930
Orthopristis chrysoptera	6	160	22	769	2032	2942	7244	602	8048
Pagurus pollicaris	0	333	170	1877	255	880	4415	51	331
Palaemon spp.	131	172	216	163	7608	2287	71	18,045	4828
Penaeus aztecus	16,618	39,036	20,849	51,301	159,906	118,224	51,828	15,437	11,157
Penaeus duorarum	0	224	523	2120	6594	11,116	14,865	2935	5001
Penaeus setiferus	41,942	101,792	40,600	39,604	56,735	52,643	17,524	6553	2336
Peprilus burti	107	2718	60	8,806	1270	3650	5299	11	117
Pogonias cromis	2620	668	2249	97	1197	521	449	6262	110
Polydactylus octonemus	32	238	103	2744	863	1770	2813	88	327
Rangia cuneata	37,377	16,108	7	30	5806	6	6	1	0
Rangia flexuosa	29	10,890	1	24	2061	126	0	0	0
Selene setapinnis	230	1236	60	4484	121	306	3563	0	215
Solenosteira cancellaria	0	4	62	173	19	147	8752	6	100
Sphoeroides parvus	159	1622	260	2695	1666	2402	1109	478	411
Squilla empusa	46	511	389	2019	553	1362	2114	59	266
Stellifer lanceolatus	1828	1443	947	2038	81	88	585	4	148
Tozeuma carolinense	0	0	2	19	319	11	5	3395	3320
Trichiurus lepturus	372	1819	545	3225	268	1760	4324	75	376

Codes for bays are as follows: *SL*, Sabine Lake; *GB*, Galveston Bay; *EMB*, East Matagorda Bay; *WMB*, West Matagorda Bay; *SAB*, San Antonio Bay; *AB*, Aransas Bay; *CCB*, Corpus Christi Bay; *ULM*, Upper Laguna Madre; and *LLM*, Lower Laguna Madre

differentiation between early and late period. The species with the largest positive loading on PC1 was Gafftopspail Catfish (0.393) and the species with the largest negative loading on PC1 belonged to Atlantic rangia (– 0.343).

Atlantic rangia, blue crab, and lesser blue crab, the three species exhibiting the sharpest drop in annual CPUE, decline by about 2% per year. The declines of *Callinectes* crabs began in the 1980s (Fig. 6). A similar pattern of decline was

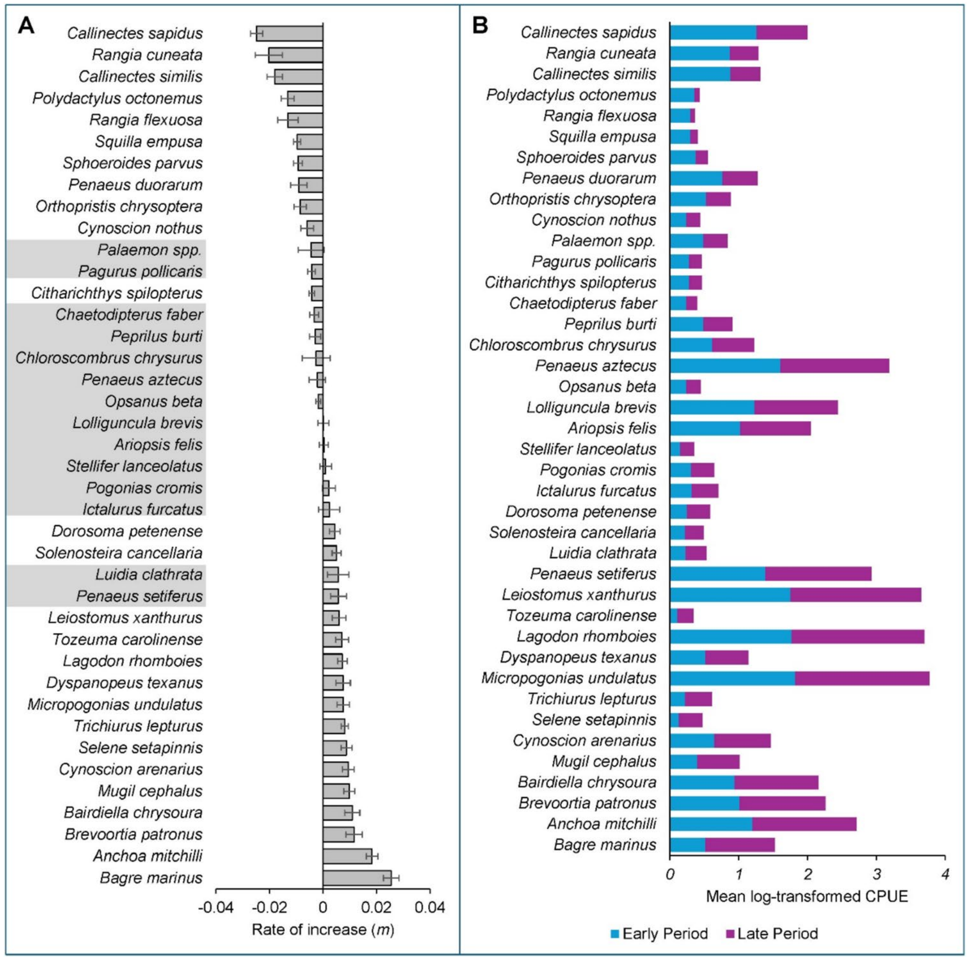

Fig. 4 Rates (m) of increase or decrease of 40 species based on regressing CPUE against year (**A**) and the results from SIMPER showing the mean CPUE of each species in early and late Periods (**B**). Error bars represent standard error from simple linear regression. Species names within gray boxes represent taxa with temporal trends that were not statistically significant. Blue and purple colors represent the mean CPUE of each species in the early and late periods, respectively

also observed in the mantis shrimp (*Squilla empusa*). The coastwide annual CPUE of Atlantic rangia varied widely between 1986 and 2005, but sharp decline in abundance began 2006 with only modest recovery since 2015. Species showing positive temporal trends in abundance were generally characterized by gradual increases in annual CPUE. Gafftopsail Catfish (*Bagre marinus*) and Bay Anchovy were notable exceptions to this trend and both species increased sharply after 2015. The annual CPUE of Gafftopsail Catfish increased about 3% per year and the annual CPUE of Bay Anchovy by about 2% year, whereas most species exhibiting positive CPUE trends increased by 1% per year. Changes in the annual CPUE of commercially important species of penaeid shrimps (*Penaeus aztecus*, *P. duorarum*, and *P. setiferus*) were relatively modest compared with sharp declines in blue crab and mantis shrimp.

Significant temporal trends in length were observed in 20 species. Nine species exhibited decreases in mean length, of which five were macro-invertebrates and four were fishes (Table 4). Of the 11 species that exhibited increase in length, only two were macro-invertebrates: gray sea star (*Luidia clathrata*) and white shrimp. Cancellate cantharus (*Solenosteira cancellaria*), Silver Perch (*Bairdiella chrysoura*), and Atlantic Cutlassfish (*Trichiurus lepturus*) underwent reductions in mean length while simultaneously increasing in annual CPUE.

Total annual CPUE ($F_{1,36} = 27.0$, $R^2 = 0.43$, $P < 0.001$), mean community length ($F_{1,36} = 12.1$, $R^2 = 0.25$, $P < 0.001$), and pelagic-demersal ratio ($F_{1,36} = 31.4$, $R^2 = 0.47$, $P < 0.001$) increased from 1986 to 2023, whereas the macro-invertebrate-fish ratio ($F_{1,36} = 43.8$, $R^2 = 0.55$, $P < 0.001$), Shannon diversity index ($F_{1,36} = 22.8$, $R^2 = 0.39$, $P < 0.001$), and taxonomic distinctness ($F_{1,36} = 47.0$, $R^2 = 0.57$, $P < 0.001$) decreased over the same period (Fig. 7). The number of commercial bait licenses issued by TPWD declined from a high of 3402 in 1987 to 328 in 2021. Total metric tons of oysters harvested commercial varied considerably across the time series but exhibited no discernible pattern (Fig. 8). The indices of the two climatic oscillations exhibited opposing trends. The AMO index increased, whereas the index of PDO underwent an overall decline. All community metrics and PC1 were significantly correlated with the AMO index ($R^2 \geq 0.15$, $P \leq 0.015$ in each case) and the number of commercial bait licenses issued per year ($R^2 \geq 0.12$, $P \leq 0.038$;

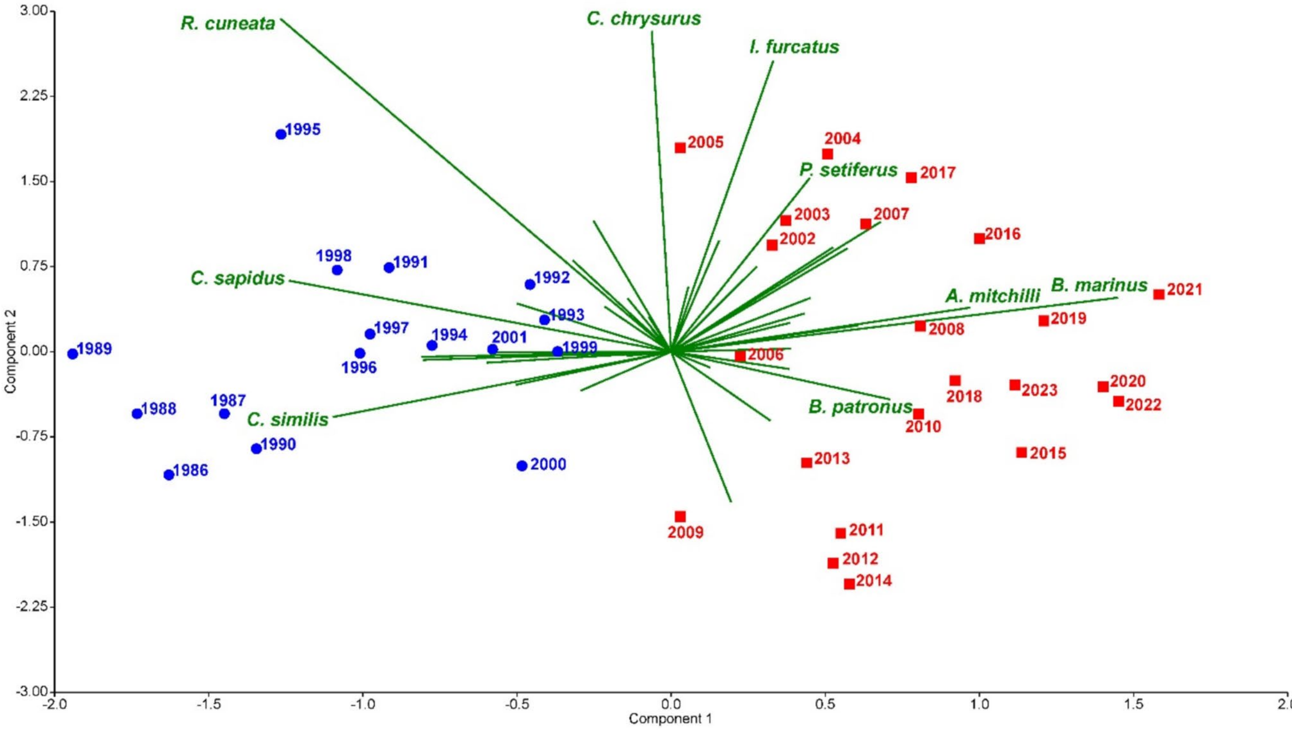

Fig. 5 Biplot of result of PCA demonstrating the relationships among years and the 40 most common taxa captured in fishery-independent trawls in Texas inshore waters. Year labels are blue (early period, 1986–2001) and red (late period, 2002–2023). Green vector arrows represent individual species. To ensure clarity, only species with the principal component scores ≥|3| are labeled

Table 5). The community metrics (excluding the pelagic-demersal ratio) and PC1 were also significantly correlated with the PDO index ($R^2 \geq 0.13$, $P \leq 0.027$). Taxonomic distinctness ($R^2 \geq 0.14$, $P \leq 0.020$) and mean community length ($R^2 \geq 0.14$, $P \leq 0.022$) were the only dependent variables significantly correlated with commercial oyster harvest.

Discussion

This study examined spatial patterns and temporal trends of trawl-associated fishes and macro-invertebrates captured in fishery-independent trawl sampling and assessed changes in community structure. Trawl-associated taxa were dominated by a subset of 40 species, of which Atlantic Croaker, Spot, and Pinfish were the most abundant. Spatial structuring of trawl-associated taxa was driven first by a north–south latitudinal gradient of temperature and salinity, and secondarily by mean depth. Several species of fish increased in CPUE over the time series, whereas macro-invertebrates either remained stable or declined in CPUE. The overall species composition of our focal group was qualitatively similar in comparison to bycatch composition in Texas commercial shrimp trawls (Fuls et al., 2002). The most abundant species in our dataset were also the most abundant species in fishery-independent trawl samples from other GoM estuaries in Louisiana, Mississippi, Alabama, and Florida (Brown et al., 2013). A shift in community structure from 1986 to 2023 was apparent from the results of cluster analysis and PCA, which showed clear division between earlier (1986–2001) and later years (2002–2023). The change in community structure was also reflected in opposing trends in community metrics (increasing total CPUE, mean community length, and pelagic-demersal ratio; and decreasing invertebrate-fish ratio, Shannon diversity index, and taxonomic distinctness) as well as trends in the CPUE of specific taxa. Strong positive correlations between PC1 and community metrics and predictor variables suggest that changes in species CPUE and community composition are associated with warming climate and declines in some commercial fisheries.

Differences in bay-specific raw catch data as well as divergent multivariate ordination patterns in the RDA demonstrated that the sampling method and effort of the TPWD Coastal Fisheries fishery-independent data collection program provides sufficient data sensitivity to detect the expected biotic and hydrological differences between the nine major bays on the Texas coast. The salinity and temperature gradient of the Texas coast observed in the plot of the RDA scores was mirrored by similar clinal gradients

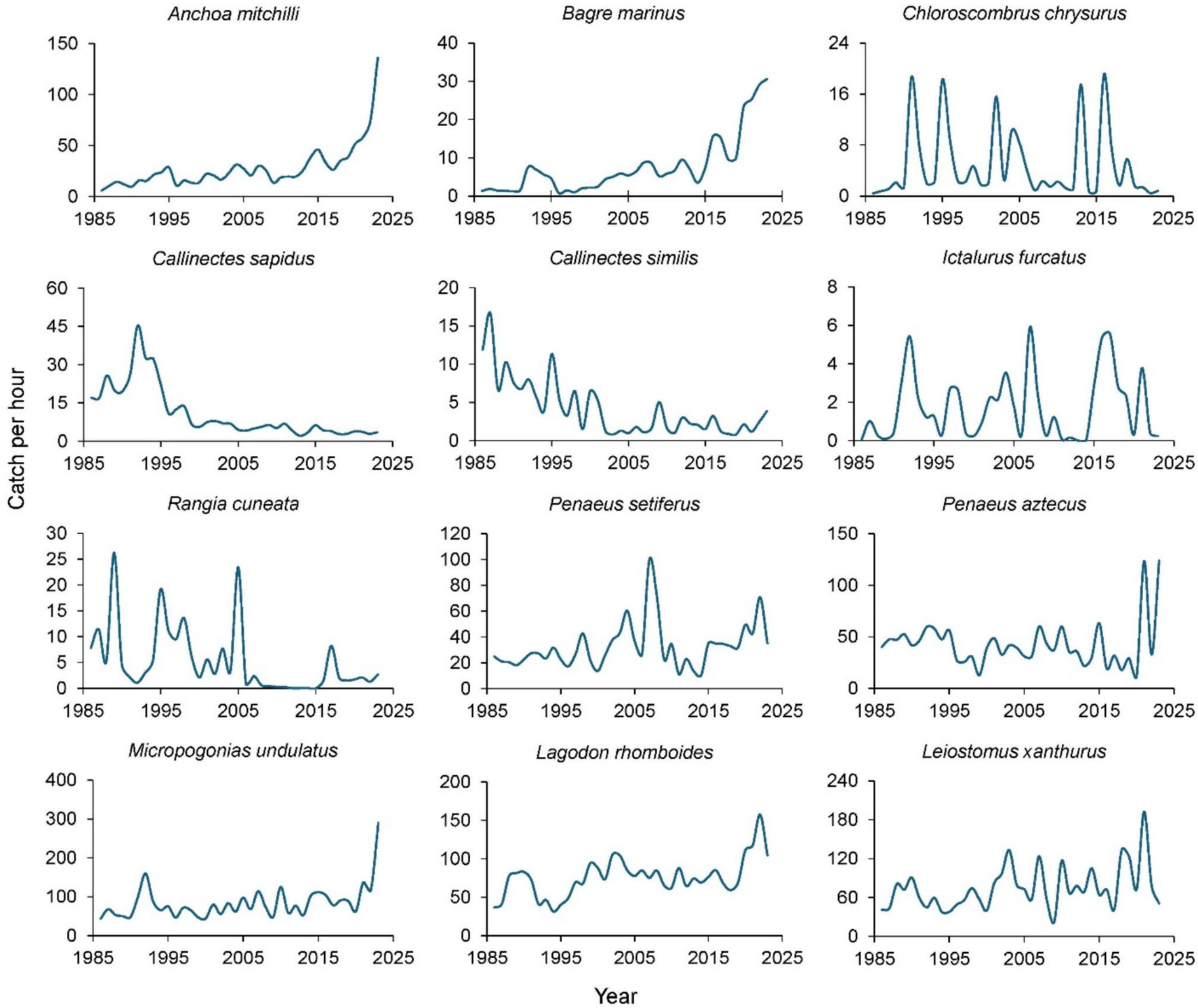

Fig. 6 Annual trends in abundance based on catch-per-unit effort for selected species, including the three most abundant fishes, the two most commercially important penaeid shrimps in the Gulf of Mexico, and those taxa that contributed the most to the ordination of the SIMPER analysis (individual contribution of ≥ 4% to differentiation between the 1986–2001 and 2002–2023) or that had loadings of ≥|0.3| on principal component 1 or 2 of the PCA

in the total catch of several focal species. Larger catches of Atlantic rangia, white shrimp, Gulf Menhaden, Sand Seatrout, and Atlantic Croaker occurred in the upper coast bays but were lower in southern bays. A reversal of this trend was observed among species more closely associated with Aransas and Corpus Christi Bays and the Upper and Lower Laguna such as Silver Perch, Pigfish, pink shrimp, Pinfish, and Gulf grassflat crab. Past research has documented how salinity and temperature influence the CPUE and distribution of fishes and macro-invertebrates in Texas bays (i.e., Armstrong, 1987; Froeschke et al., 2010; McFarlane et al., 2015; Olsen, 2019). The effect of depth on the spatial distribution and abundance of fishes and macro-invertebrates in Texas estuaries is not as well-documented; however, a recent comparison of the abundance of 57 species among estuarine systems across the GoM found that depth was far less important than salinity and temperature (Miller et al., 2018).

Based on the seemingly high sensitivity to spatial differences, it could be further inferred that these data are similarly sensitive to temporal change which was the major focus of this study. The community structure of fishes and macro-invertebrates in Texas estuaries shifted substantially between the early (1986–2001) and late (2002–2023) periods. Positive trends of total CPUE, mean community length, and pelagic-demersal ratio were largely driven by increased abundance and length among fishes. Conversely, the negative trends of the Shannon diversity index and taxonomic distinctness were tied to decreased CPUE of macro-invertebrates but further

Table 4 Results of regressing mean TL (mm) against time (years)

Species	N	R^2	Slope (m)	P-value	Trend
Anchoa mitchilli	170,254	0.006	−0.021	0.637	
Ariopsis felis	92,504	0.420	1.010	<0.001	Increasing
Bagre marinus	53,948	0.090	0.224	0.073	
Bairdiella chrysoura	101,760	0.130	−0.191	0.029	Decreasing
Brevoortia patronus	94,472	0.080	0.241	0.085	
Callinectes sapidus	109,797	0.002	−0.035	0.814	
Callinectes similis	32,999	0.690	−0.525	<0.001	Decreasing
Chaetodipterus faber	6990	0.400	0.672	<0.001	Increasing
Chloroscombrus chrysurus	19,571	0.350	0.506	<0.001	Increasing
Citharichthys spilopterus	7992	0.110	−0.109	0.046	Decreasing
Cynoscion arenarius	49,661	0.030	0.135	0.322	
Cynoscion nothus	6906	0.090	−0.372	0.061	
Dorosoma petenense	10,738	0.220	0.278	0.003	Increasing
Dyspanopeus texanus	16,906	0.030	−0.017	0.269	
Ictalurus furcatus	9658	0.009	0.421	0.562	
Lagodon rhomboides	271,280	0.003	−0.017	0.762	
Leiostomus xanthurus	308,696	0.220	0.354	0.003	Increasing
Lolliguncula brevis	145,626	0.060	−0.055	0.135	
Luidia clathrata	8386	0.110	0.472	0.043	Increasing
Micropogonias undulatus	382,185	0.010	0.049	0.591	
Mugil cephalus	20,225	0.002	−0.056	0.803	
Opsanus beta	6720	0.060	−0.413	0.151	
Orthopristis chrysoptera	17,426	0.020	−0.114	0.384	
Palaemon spp.	211,692	0.020	−0.010	0.393	
Penaeus aztecus	256,811	0.380	−0.229	<0.001	Decreasing
Penaeus duorarum	37,134	0.040	0.097	0.206	
Penaeus setiferus	234,108	0.290	0.229	<0.001	Increasing
Peprilus burti	18,996	0.190	0.294	0.006	Increasing
Pogonias cromis	11,773	0.180	1.642	0.008	Increasing
Polydactylus octonemus	8211	<0.001	0.023	0.961	
Rangia cuneata	14,269	0.270	−0.262	0.001	Decreasing
Rangia flexuosa	2351	0.190	−0.453	0.006	Decreasing
Selene setapinnis	8891	0.230	0.328	0.002	Increasing
Solenosteira cancellaria	221,057	0.120	−0.046	0.031	Decreasing
Sphoeroides parvus	9935	0.040	−0.153	0.221	
Squilla empusa	6979	0.100	0.182	0.051	
Stellifer lanceolatus	5072	0.030	0.244	0.267	
Tozeuma carolinense	2481	0.030	0.096	0.293	
Trichiurus lepturus	11,895	0.270	−1.169	0.001	Decreasing

Provided are the number of individuals measured (N); the slope (m), R^2, and P-value of the regression; and the trend (increasing or decreasing) for species exhibiting significant ($P<0.05$) temporal trends in length ($n=18$)

amplified by the declines of several demersal fishes. Declining Shannon diversity observed in this study contrasts with that of Fujiwara et al. (2019) who observed an increase in the diversity of fish and macro-invertebrates. One possible explanation for this difference is that Fujiwara et al. (2019) and the present study examined different biotic communities. Fujiwara et al. (2019) was based on data derived from bag seines, which is representative of organisms associated with shallow shoreline environments (small-bodied taxa and juveniles of larger species), whereas trawl data used in this study represents information on species typical of deeper water (usually larger-bodied organisms, and later life stages of small-bodied taxa). Shoreline and deep-water communities may respond differently to climatic fluctuations and

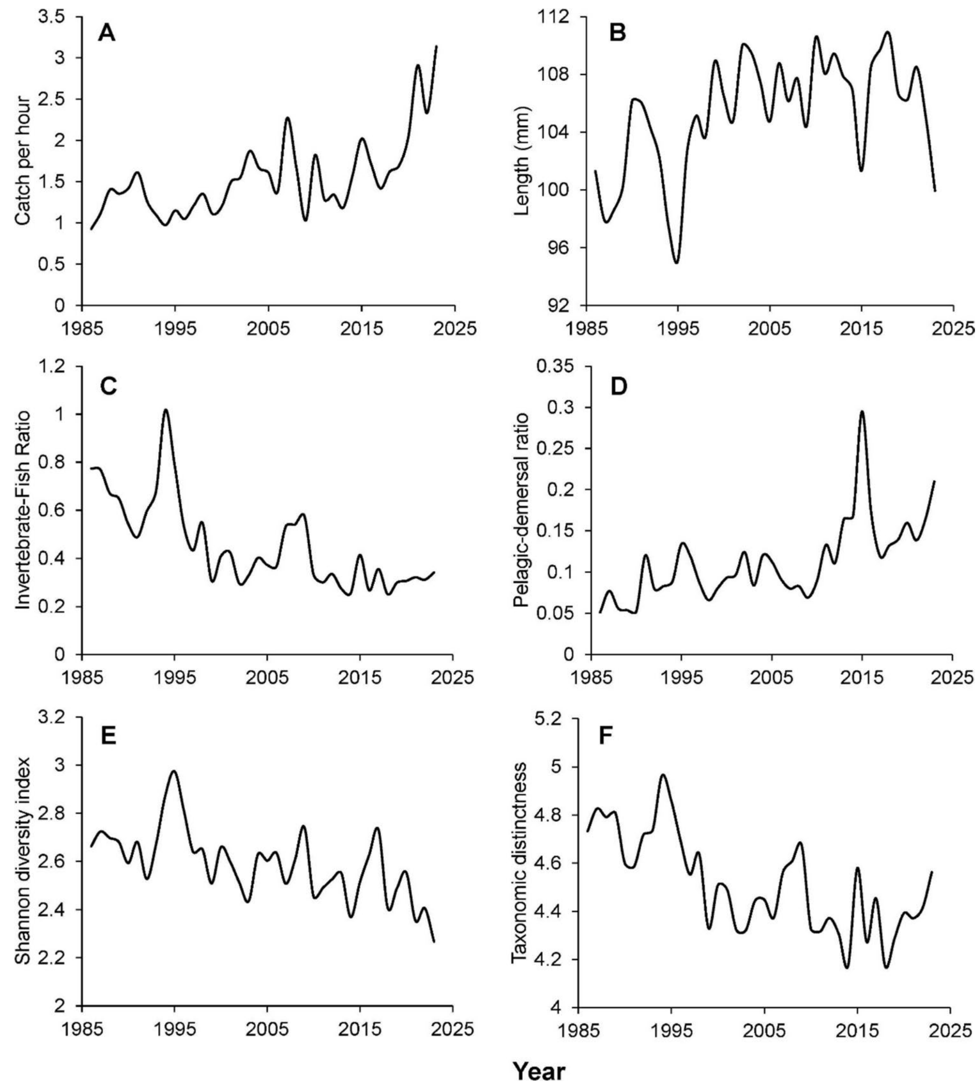

Fig. 7 Trends in community metrics calculated for the Texas coast: **A** total CPUE, **B** mean community length, **C** invertebrate-fish ratio, **D** pelagic-demersal ratio, **E** Shannon diversity index, and **F** taxonomic distinctness

anthropogenic impacts. Limiting our study to 40 species may have also biased our results. Preliminary analysis using the entire dataset, however, also yielded a declining Shannon diversity index and an increase in total CPUE; therefore, it is unlikely that including the entire dataset would have fundamentally changed this result.

Changing composition of biotic communities is often influenced more by the reordering of species abundances rather than absolute loss of species (Jones et al., 2017), which in turn results in homogenization of communities and overall loss in species diversity at regional scales (Engel et al., 2020). Our results suggest that much of the community reorganization is due to increased prevalence and abundance of primarily low-trophic (Striped Mullet, Gulf Menhaden, and *Bay Anchovy*) and mid-trophic level (sciaenids, Pinfish, and Gafftopsail Catfish) fishes and declines of several macro-invertebrates. The shift in community structure and changes in CPUE observed in this study parallels changes in estuarine shoreline fishes and macro-invertebrates that have taken place in the last 40 years in Texas (Fujiwara et al., 2019, 2022; Pawluk et al., 2022). Long-term (1985–2015) TPWD fishery-independent bag seine data indicated that species close to the southern extent of their geographic distributions underwent declines in prevalence and range contractions (Fujiwara et al., 2019). Analysis of TPWD fishery-independent gill net data collected since the 1980s has corroborated this finding and have documented declines in species more closely associated with colder water, such as Southern Flounder (*Paralichthys lethostigma*) and increased dominance of the estuarine fish community by warmwater species such as snooks (*Centropomus* spp.), ladyfishes (*Elops* spp.), gray snapper (*Lutjanus griseus*), Gafftopsail Catfish, and various elasmobranchs (Ceron et al., 2023; Pawluk et al., 2022; Plumlee et al., 2018). Gafftopsail Catfish exhibited the greatest increase in CPUE among the 40 species examined in our study. Increased CPUE of Gafftopsail Catfish has been observed in previous studies based on different sampling gears (Cates et al., 2024; Ceron et al.,

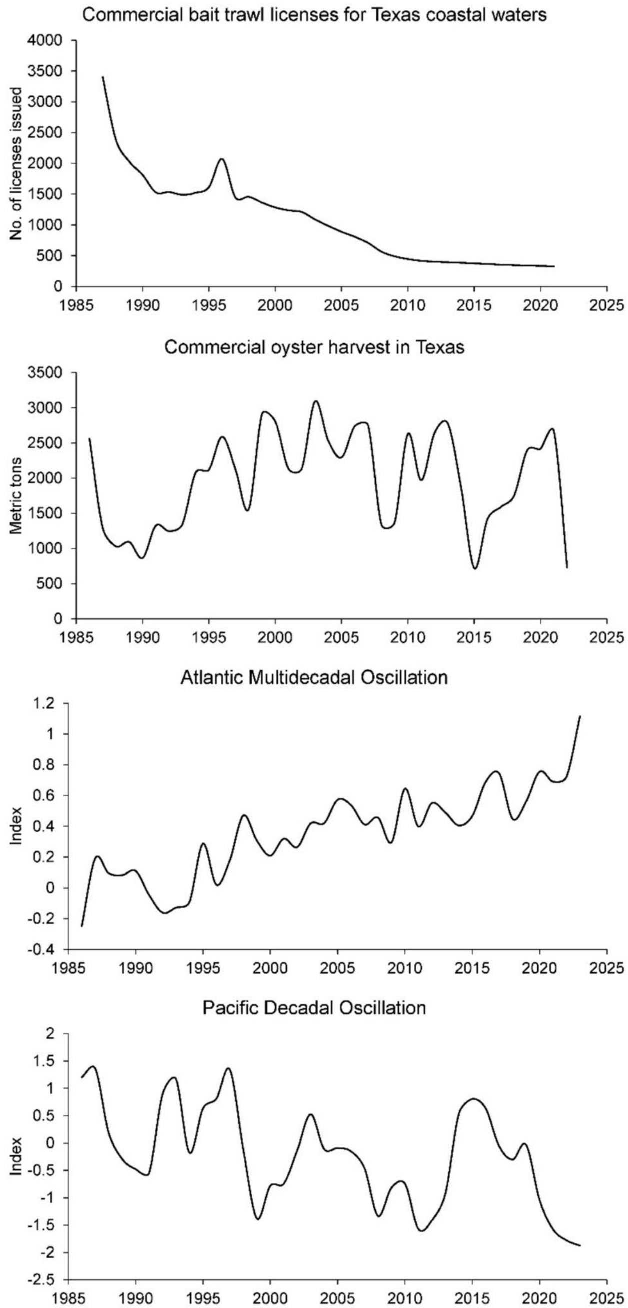

Fig. 8 Trends in predictor variables (1986–2023), including number of commercial bait trawl licenses issued for Texas coastal waters, commercial oyster harvest, and indices of the Atlantic Multidecadal and Pacific Decadal Oscillations

Table 5 Results of regressing PC1 and community metrics against predictor variables, including the Atlantic Multidecadal Oscillation (AMO) index, Pacific Decadal Oscillation (PDO) index, the number of bait licenses issued each year by TPWD for Texas coastal waters, and the annual harvest in metric tons of oysters in Texas coastal waters

Dependent variable	R^2	*P*-value	Trend
AMO			
PC1	0.60	< 0.001	Positive
Total CPUE	0.32	< 0.001	Positive
Shannon diversity index	0.30	< 0.001	Negative
Taxonomic distinctness	0.36	< 0.001	Negative
Community mean size	0.15	0.015	Positive
Invertebrate-fish ratio	0.47	< 0.001	Negative
Pelagic-demersal ratio	0.31	< 0.001	Positive
PDO			
PC1	0.22	0.003	Negative
Total CPUE	0.13	0.025	Negative
Shannon diversity index	0.20	0.005	Positive
Taxonomic distinctness	0.13	0.027	Positive
Community mean size	0.14	0.022	Negative
Invertebrate-fish ratio	0.18	0.008	Positive
Pelagic-demersal ratio	0.02	0.409	Negative
Bait licenses			
PC1	0.79	< 0.001	Negative
Total CPUE	0.12	0.038	Negative
Shannon diversity index	0.29	0.001	Positive
Taxonomic distinctness	0.50	0.001	Positive
Community mean size	0.44	< 0.001	Negative
Invertebrate-fish ratio	0.47	< 0.001	Positive
Pelagic-demersal ratio	0.27	0.001	Negative
Oyster harvest			
PC1	0.04	0.264	Positive
Total CPUE	0.09	0.574	Negative
Shannon diversity index	0.02	0.403	Negative
Taxonomic distinctness	0.14	0.020	Negative
Community mean size	0.14	0.022	Positive
Invertebrate-fish ratio	0.08	0.091	Negative
Pelagic-demersal ratio	0.01	0.555	Negative

2023; Pawluk et al., 2022). The increase of warmwater and tropical species of fishes in Texas estuaries has been attributed to a warmer climate and milder winters (Ceron et al., 2023; Fujiwara et al., 2019; Pawluk et al., 2022). Milder winters in Texas estuaries and the open GoM may enhance survival of larvae and juveniles of tropical and warmwater taxa and simultaneously cause stress for others that are at or nearing their upper limit of thermal tolerance, or that otherwise require cold temperatures during parts of their life history (Anderson et al., 2023a; Erickson et al., 2021).

Occupancy modeling in a previous study predicted increased prevalence of blue crab and decreased prevalence of Bay Anchovy (Fujiwara et al., 2019). Although occupancy and prevalence are not directly comparable to abundance, these concepts are related in that increasing abundance usually leads to increased prevalence. The results of Fujiwara et al. (2019) regarding blue crab and bay anchovy conflict with our findings, which showed blue crabs underwent the greatest decrease in CPUE and Bay Anchovy exhibited the second greatest increase in abundance. The decline of blue crabs in the western Gulf of Mexico has been previously documented (Perry & VanderKooy, 2015; Perry et al., 2022) and CPUE of blue crabs in TPWD bag seines has decreased from 1982 to 2024 (data available from authors upon request). The discrepancy between Fujiwara et al. (2019) and this study regarding trends in blue crabs may have resulted from the type of data and parameters used in occupancy modeling versus observations of empirical data (CPUE) used in this study. One possible explanation for the discrepancies regarding bay anchovy may be differing trends in abundance of this species in bag seines (used by Fujiwara et al., 2019) versus trawls (this study). The CPUE of bay anchovies in TPWD bag seines exhibits as slight decline, which may be due to increased growth of juveniles and subsequent rapid shift to deeper waters rather than an overall decline in abundance. A faster growth rate was invoked as the most likely explanation for the decline of spot in bag seine collections from Texas estuaries despite increased abundance of this species in trawls and gill nets (Williford & Anderson, 2025).

Shifts in community composition and abundance of certain species have taken place during a period of declining shrimping effort, increased oyster harvest, and changes in climate. Of the four predictor variables considered, commercial bay shrimping effort (represented by the number of bait licenses) and AMO appear to be the main drivers shaping the community structure of fishes and macro-invertebrates in Texas estuaries. Commercial shrimp trawling has effects on bycatch species through direct mortality (Diamond et al., 1999; Fuls et al., 2002) and indirectly through habitat alteration and degradation (Auster & Langton, 1999; Smith et al., 2000; Thrush & Dayton, 2002). Additionally, bottom trawl fisheries (such as the inshore trawl fishery in Texas) can have indirect negative effects on body size and condition of demersal predators by decreasing the availability of benthic prey (Diamond et al., 1999; Hiddink et al., 2011; Wells et al., 2008). Reductions in commercial shrimp trawling effort may have had a disproportionate positive impact on mesopredators in relation to the targeted shrimp species. Shrimp and other crustaceans represent major prey item for Pinfish (Stoner, 1980), Atlantic croaker (Akin & Winemiller, 2012; Willis et al., 2015), spot (Akin & Winemiller, 2012), sand seatrout (Barnes, 2014), and marine catfishes (Osowski et al., 2023; Rudershausen & Locascio, 2001). Declines in shrimping effort may have reduced a constraint on the population growth of Atlantic Croaker and other mesopredators leading to increased predation on shrimp and other crustaceans, resulting in population declines or lack of population growth in various species of shrimp and crabs. Reduced bycatch mortality and increased prey availability may have also had a favorable impact on growth. This hypothesis, however, does not explain the decline in CPUE of Bay Whiff, Pigfish, Atlantic Threadfin (*Polydactylus octonemus*), and Least Puffer, which have also been documented as common in shrimp trawl bycatch (Fuls et al., 2002). Although some common bycatch organisms may have enjoyed a benefit from reduced shrimping effort over our time series, others did not, and this contrast could potentially be related to the interplay between fishing impacts (in this case, declining fishing effort) versus climate.

The shift of the AMO to its current warm phase seems to have driven as much of the biotic changes in Texas estuaries as the decline of shrimping has over the past 38 years. The warm phase of the AMO is linked to higher sea surface temperatures in the North Atlantic (Allard et al., 2016; Drinkwater et al., 2014; Knudsen et al., 2011) and warmer land temperatures and reduced precipitation over much of North America (Endfield et al., 2001; Feng et al., 2010; O'Reilly et al., 2017). Summer and winter temperatures in Texas estuaries have increased since the early 1990s (Anderson et al., 2023a; Bugica et al., 2020; Tolan & Fisher, 2008). Previous studies have concluded that warmer temperatures have played a major role in restructuring biotic communities in estuaries (Sobocinski et al., 2013; Munk et al., 2014; Fujiwara et al., 2019; Kimball et al., 2020; Pawluk et al., 2022). Warming climate is a major factor contributing to the increased abundance of tropical and subtropical taxa such as Gray Snapper (*Lutjanus griseus*, Tolan & Fisher, 2008; Anderson et al., 2022), snooks (*Centropomus* spp., Anderson et al., 2020; Getz et al., 2021), and ladyfishes (*Elops* spp., Williford et al., 2022) in the Gulf of Mexico. Milder winters in estuaries and the GoM and Western Atlantic may enhance survival of larvae and juveniles of some taxa and simultaneously cause stress for others that are at or nearing their upper limit of thermal tolerance, or that otherwise require cold temperatures during parts of their life history (Anderson et al., 2023a; Fujiwara et al., 2022; Plumlee et al., 2024; Sluis et al., 2025).

The overall weak correlation of PC1 and community metrics with commercial oyster harvest was somewhat surprising given the importance of oyster reefs as important habitat for adult and juvenile nekton (Balboa et al., 2024; Coen et al., 1999; Stunz et al., 2010). This is likely due to the fact than none of the taxa, except for the Gulf Toadfish (Bass & Guillory, 1979), are regular residents of oyster reefs, and, in fact, they use a wide range of other habitats. The use of oyster reefs by Gulf Toadfish is mostly restricted to the spawning season (Barimo et al., 2007). Much like the common practice in the commercial industry, TPWD fishery-independent trawls generally avoid operating over oyster reefs, such that the species expected to be associated with those habitats are not well represented. Similarly, PDO appears to have minimal influence on community structure in Texas' estuaries, which may be due to the shorter duration of PDO warm and cool phases compared to the AMO.

It is possible that any signal that could be expected from the short-term impacts of PDO have been swamped by the longer-term community reorganization observed here and driven by gradual declines in inshore commercial trawling and the AMO.

Regarding this last point, the shift of the AMO to a warm phase and the reduction of shrimping effort has occurred during a time that has coincided with increased industrialization and urbanization, and human population growth in coastal Texas. Industrialization and urbanization in coastal areas often lead to increased eutrophication of estuaries, which in turn can alter the structure of estuarine biotic communities (Yashuara et al., 2007; Gilbert, 2010; Shan et al., 2013; Freeman et al., 2019). Although nutrient loading has undoubtedly increased in Texas estuaries, only Baffin Bay (a secondary arm of the Upper Laguna Madre), Oso Bay (a secondary extension of Corpus Christi Bay), and heavily urbanized Galveston Bay are considered eutrophic (Bugica et al., 2020). Eutrophic systems are often dominated by detritovorous and omnivorous species, with large carnivorous species becoming rare (de Carvalho et al., 2020). Increased abundance of striped mullet, a detritivore (Crosetti & Blaber, 2015), and omnivorous species such as Atlantic Croaker (Nye et al., 2011) and Pinfish (Montgomery & Targett, 1992) could be interpreted as evidence of increased eutrophication. However, the continued presence and increased abundance of large predatory fish such as Bull Shark (*Carcharhinus leucas*, Froeschke et al., 2012), Alligator Gar (*Atractosteus spatula*, Daugherty et al., 2017), and Red Drum (*Sciaenops ocellatus*, Anderson et al., 2023b) in Texas estuaries suggest that eutrophication may play a smaller role in the restructuring of fish communities than either climate or commercial fishing. Unfortunately, long-term data ($\geq$ 30 years) that could be used to assess levels of eutrophication in Texas estuaries and its effect on the community structure of fish and macro-invertebrates is lacking. Other factors that have likely contributed to reshaping the community structure of fishes and macro-invertebrates in Texas estuaries include changes in the extent and composition of seagrass, salt marsh, and mangroves, which provide important foraging and nursery habitat for fish and macro-invertebrates (Bloomfield & Gillanders, 2005; Scheffel et al., 2018; Armitage et al., 2021; zu Ermgassen et al., 2021), and the impact of increased salinity caused by reduced freshwater inflow from rivers due to droughts and human activities (Getz & Eckert, 2023; Kim & Montagna, 2009; Pollack et al., 2009; Sklar & Browder, 1998). Unfortunately, the long-term data records needed to incorporate those factors into our analysis are lacking.

Ongoing climatic change due to both natural and anthropogenic factors may limit the effectiveness of management strategies to preserve or enhance populations of declining species. Enhancing and protecting fine-scale habitat heterogeneity of estuaries may buffer the effects of continued warming. For instance, environmental heterogeneity can promote phenotypic plasticity and reduce the risk of short-term extirpation for some species (e.g., de Souza et al., 2023). Habitat loss or conversion from climate, industrial development, or other factors over the time period examined here suggests a trend towards more homogenous estuarine habitats, which will ultimately impact community and species-specific resilience and in some cases lead to threat of ecosystem collapse (Mahoney & Bishop, 2017; Thrush et al., 2008). Climate change specifically is expected to have a net-negative impact on habitat vulnerability (Farr et al., 2021), and probably the most notable implication from the current study is that climate now seems to have an impact similar in magnitude to fishing in restructuring biotic communities in estuaries of the northern GoM. Fishing has historically been considered one of the main drivers of change either at the community or species-specific scales, but persistent climate change is at least as important as a consideration for management, and changing climate should be elevated in estuarine conservation efforts as a primary threat to community resilience.

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Author Contribution Each of the authors contributed equally to this work. Both authors read and approved the current version of the manuscript.

Data Availability Data is available from the authors upon request.

Declarations

Ethical Approval Collection of and handling protocols for fish and invertebrates were in accordance with ethical guidelines stipulated by a Federal Sport Fish Restoration grant agreement, Texas Parks and Wildlife Department TX F-281-M, as well as a federal permit for the handling of endangered and threatened species issued by the Department of the Interior, permit number TE814933-0.

Competing Interests The authors declare no competing interests.

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