*Marine and Coastal Fisheries*, 2025, **17**, vtaf033
https://doi.org/10.1093/mcfafs/vtaf033
Advance access publication: September 29, 2025
**Article**

# Assessing the resistance and resilience of recreationally important fish species to extreme events in coastal Texas

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## ABSTRACT

**Objective:** Extreme events, such as hurricanes and winter storms, are known to disrupt coastal ecosystems in diverse ways, often requiring specific management and conservation actions to counter their negative effects. However, little is known about how the impacts of extreme events vary by species and over space. We used the vast Texas coastline as a case study, given the area's importance for recreational fisheries and its vulnerability to several types of extreme events, to evaluate species responses across bays.

**Methods:** We used long-term fisheries-independent bag-seine data (2007–2016 and 2010–2019) to analyze changes in abundance after Hurricane Harvey and the 2021 Texas freeze brought on by Winter Storm Uri. We selected data for the top recreational saltwater fish species, including the juvenile Red Drum *Sciaenops ocellatus*, Spotted Seatrout *Cynoscion nebulosus*, Black Drum *Pogonias cromis*, and Southern Flounder *Paralichthys lethostigma*. We analyzed the percent change of catch per unit effort in each major bay from a 10-year baseline period preceding each event to the first year after the event (resistance) and the second year after the event (resilience) to ascertain a storm effect. Additionally, we ran a generalized linear mixed model with a negative binomial distribution to further understand how species' counts compared in nonstorm, storm, and poststorm periods.

**Results:** Resistance and resilience to each event were variable among species and individual bay systems along the coast. Spotted Seatrout experienced the greatest declines in southern bays after the 2021 freeze but were resilient to both Hurricane Harvey and the freeze. Red Drum were resistant to the effects of both Hurricane Harvey and the 2021 freeze but lacked resilience following the freeze, particularly in the northern bays. In contrast, Black Drum were resistant and resilient after the 2021 freeze but lacked both resistance and resilience after Hurricane Harvey. Southern Flounder was resistant and resilient following both events.

**Conclusion:** Our results demonstrate the importance of evaluating storm responses spatially across major bays, as information can be used to create specific placed-based management plans. Our results provide additional evidence of freeze events negatively affecting some estuarine fish, especially those with limited movement behaviors like the Spotted Seatrout. Identifying species-specific responses to extreme events can support and inform fishery management strategies—such as place-based and temporal harvest restrictions—especially as global climate change threatens to increase the frequency and severity of extreme events.

**KEYWORDS:** Black Drum, *Cynoscion nebulosus*, extreme events, fisheries management, fisheries-independent data, freeze event, hurricanes, *Paralichthys lethostigma*, *Pogonias cromis*, Red Drum, *Sciaenops ocellatus*, Southern Flounder, Spotted Seatrout

## LAY SUMMARY

Hurricanes and winter storms have strengthened due to climate change and can negatively impact marine fishes. By using fisheries catch data to compare how different fish species respond to storms on the Texas Gulf Coast, we can improve fisheries management in a changing world.

## INTRODUCTION

Extreme events, such as major hurricanes and winter storms, can disrupt coastal ecosystems in diverse ways, ranging from habitat destruction to the mass mortality of fish (Bailey & Secor, 2016; Matich et al., 2020; Ummenhofer & Meehl, 2017; van Oldenborgh et al., 2017). Further, they are expected to increase in severity and frequency due to climate change and rising ocean temperatures (Bailey & van de Pol, 2016; International Panel on Climate Change, 2018; Trenberth et al., 2018; van Oldenborgh et al., 2017). Additionally, extreme events can

**Received:** November 11, 2024. **Revised:** April 9, 2025. **Editorial decision:** July 24, 2025

rapidly and significantly change environmental variables along coastlines, such as water temperature, salinity, and nutrient inputs (Du & Park, 2019; Poirrier et al., 2008; Sasidharan & Wetz, 2022; Wetz & Yoskowitz, 2013). As a result, these rapid environmental changes pose challenges to coastal fishes by altering reproduction, recruitment, access to food, and body condition (Biggs et al., 2018; Matich et al., 2020; Smee et al., 2020; van Oldenborgh et al., 2017). Moreover, coastal fishes can be impacted by multiple types of extreme events within the same habitat. However, understanding species-specific responses following different types of events remains limited (Bailey & Secor, 2016; Bellquist et al., 2021). Currently, the majority of studies in extreme event ecology analyze single events or single species (Bailey & van de Pol, 2016), so incorporating multiple event types and multiple species will improve our understanding of how extreme events impact coastal ecosystems.

Assessing the resistance (which we define as first year poststorm) and resilience (second year poststorm) of coastal fishes requires the collection and analysis of extensive data both before and following extreme events. Long-term monitoring data, such as fishery-independent surveys conducted by state management agencies, provide an opportunity to assess disturbances over large spatial and temporal scales. These surveys are crucial for developing management strategies to address adverse impacts, including extreme events. For example, interpretations of fishery-independent data allowed managers in Florida to take specific management actions after a cold snap in 2010 to address significant declines in the recreational fishery for Common Snook *Centropomus undecimalis* (Stevens et al., 2016). Specifically, they implemented changes to the fishing bag and slot limits of Common Snook to allow recovery and closed recreational harvest in the estuaries with the largest population declines (Stevens et al., 2016). Similarly, Texas Parks and Wildlife Department (TPWD) coastal fisheries managers employed place-based closures over small areas of deep water (e.g., thermal refugia habitat such as deep wells or dredged channels) during extreme cold weather to minimize increased fishing pressure on fish seeking thermal refuge. Similarly, following a cold snap in 2021 and subsequent fishery-independent survey data showing significant declines in adult Spotted Seatrout abundance, managers at TPWD enacted expedited emergency changes to their fishing bag and slot limits (Bonnot, 2023).

To understand the resistance and resilience of coastal recreational fisheries in the context of multiple events and species, we studied the Texan coast of the Gulf of Mexico, given its vast coastline (591 km), unique estuarine environments, and extensive long-term monitoring data set from the TPWD. The Texas coast is made up of several barrier islands that create unique estuarine environments for fauna and flora (McGowen et al., 1977; Smith, 2018). Texas also experiences a variety of extreme events along its coastline, where the warm waters of the Gulf Stream often intensify tropical storms to hurricanes (Leipper & Volgenau, 1972; McGowen et al., 1977). Other extreme events in the region include floods, droughts, tornadoes, heat waves, winter storms, and cold snaps (Deng et al., 2018; Karl & Quayle, 1981; Matich et al., 2020; McEachron et al., 1994; Nielsen-Gammon, 2012; Thronson & Quigg, 2008; van Oldenborgh et al., 2017). The effects of extreme events, especially hurricanes and cold snaps, on fish abundance have been studied in other Gulf Coast states like Florida and Louisiana (Adams et al., 2012; Jane et al., 2022; Santos et al., 2016; Stevens et al., 2016), but similar events in Texas have been less well documented.

The top four recreational saltwater (i.e., coastal) fish species in Texas (by catch rate per year) are Red Drum *Sciaenops ocellatus*, Spotted Seatrout *Cynoscion nebulosus*, Black Drum *Pogonias cromis*, and Southern Flounder *Paralichthys lethostigma*. These fishes contribute billions of U.S. dollars to the state's economy through recreational fisheries (Jones & Tanyeri-Abur, 2001). Each species is also ecologically important, serving as critical trophic links in estuarine habitats between bivalves, benthic invertebrates, and small and larger fish species (Bortone, 2002; Kroetz et al., 2017). Additionally, these four species differ in various biological and physiological characteristics, such as habitat use, movement behavior, and thermal and salinity tolerances.

Overall, the biological and ecological differences among these species may result in varying responses to extreme events, but this remains largely unclear. In limited prior work, similar recreationally important fish species experienced negative effects more often following freeze events than after hurricanes. For example, regime shifts in fish community structure (Santos et al., 2016) and significant declines in Common Snook abundance occurred after a 2010 cold snap in various Floridian estuaries (Adams et al., 2012; Stevens et al., 2016). In addition, the mass mortality of adult Spotted Seatrout was documented across multiple freeze events in the Gulf of Mexico and the U.S. eastern coastline (Ellis et al., 2017; McEachron et al., 1994; Thronson & Quigg, 2008). In contrast, previous studies indicate resilience (e.g., no declines in fish abundance) following a major hurricane on the Texas coast, with species such as Spotted Seatrout continuing to spawn even as the eye of Hurricane Harvey made landfall in Rockport, Texas (Biggs et al., 2018; Matich et al., 2020). Some fish species with favorable salinity and thermal limits may be resistant and resilient to hurricanes and winter storms when able to find refuge. However, event-specific responses are still possible due to different acute stressors impacting fish species during these events (e.g., low salinity and high winds versus low temperature and freezing precipitation). Yet, even with numerous studies on life history parameters and environmental tolerances, it is still unclear if these four study species vary in their responses to different types of extreme events along the Texas coast.

In this study, we examine how important coastal recreationally harvested fish populations were affected by two extreme events: Hurricane Harvey and the 2021 Texas freeze. Hurricane Harvey made landfall on August 25, 2017, in Rockport, Texas, as a category four hurricane on the Saffir-Simpson scale (van Oldenborgh et al., 2017), while the 2021 freeze, occurring between February 11 and 20, 2021, brought snowfall and unusually low temperatures to the Texas coast (Doss-Gollin et al., 2021). Using these events as case studies, we sought to (1) investigate the relationship between the type of extreme event and species-specific responses and (2) identify spatial variation in postevent fish species responses across bay systems. We hypothesized that differences in the species' life history and biological tolerances to environmental conditions would result in unique responses to the two events (Biggs et al., 2018; Ellis et al., 2017; Matich et al., 2020; Olsen, 2014). Further, given the significant north-to-south salinity and temperature gradient along the Texas coast, we hypothesized that each species' response to these events would differ among bay systems (Smith, 2018; Stevens et al., 2016).

# METHODS

## Study area

We focused on eight major bays located along the Texas coastline in the northwestern Gulf of Mexico (Figure 1). These bays have a significant salinity and temperature gradient from north to south along the coastline, with both temperature and salinity increasing with decreasing latitude (Table 1). Bay systems on the northern coast (e.g., Sabine Lake, Galveston Bay) have lower salinities due to relatively high freshwater input, while southern bays (e.g., Matagorda Bay to the lower Laguna Madre) have limited freshwater input and high evaporation rates, resulting in relatively high salinities. These bay systems also vary in depth, surface area, and volume (Table 1; Armstrong, 1987), as well as their biogenic habitats. The northern bays are primarily characterized as coastal marshland with cordgrass (e.g., *Spartina*) and open bay bottoms (habitats created by human activity such as dredging and channels), while the southern bays are characterized as sand and mud flats and sea grass beds (Armstrong, 1987; Gonzales & Kinney, 2018; Stunz et al., 2002a). The presence of sea grass habitat follows the salinity gradient north to south along the Texas coast, as sea grasses thrive in the higher salinities and lower turbidity of the southern bays (i.e., 80% of sea grass in Texas is within the Laguna Madre system; Armstrong, 1987; Stunz et al., 2002a).

## Sampling and data collection

We used data collected by the TPWD Coastal Fisheries Division's long-term fishery-independent monitoring program (Martinez-Andrade et al., 2009) for the 10 years preceding Hurricane Harvey (2007–2016) and the 2021 freeze (2010–2019). This program has followed a standardized protocol since 1984, sampling every major bay along the Texas coastline with bag seines. The bag seines are 18.3 m long and 1.8 m deep with a 19-mm stretched nylon mesh wing and 13-mm stretched nylon mesh in the bag. A 12.2-m limit line is also strung between two poles to maintain consistent and standardized width during sampling. The bag-seine survey implements a stratified cluster sampling design within each bay with a fixed number of samples per month ($n = 20$). Sampling occurs year-round, with each monthly sample allotment divided into two parts: the first 15 d of the month, followed by the 16th through the end of the month. The sample grid is laid out as one-minute latitude by one-minute longitude and is typically sequentially numbered west to east and north to south in each bay system. Sample grids are randomly selected, and no grids are sampled more than once a month. For each sample, a bag-seine sample is pulled parallel to the shoreline for a distance of 15.2 m during the day. The shoreline is defined as the edge of the dead vegetation in cases where vegetation extends out from the shore, which ensures that heavily vegetated shorelines are included in the sampling sites. No samples were collected in any grid 2 weeks after the grid had been stocked with hatchery fish.

Before conducting the seine sampling, hydrological data at the surface, such as turbidity, temperature, salinity, and dissolved oxygen, are collected approximately 3.1 m from shore.



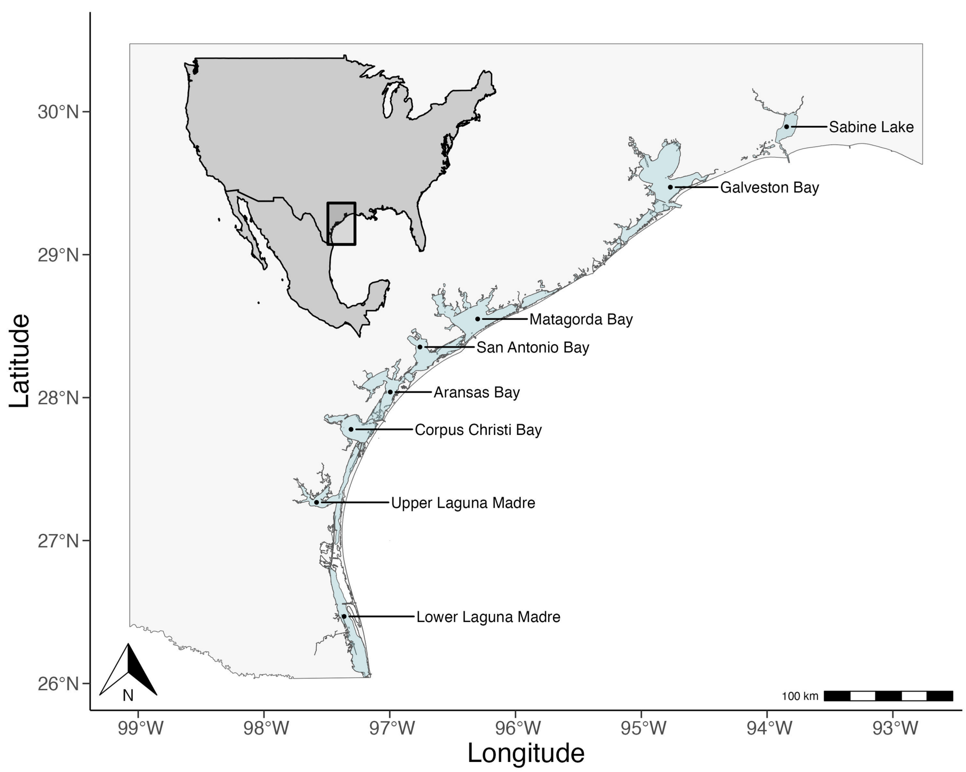


**Figure 1.** Map of the Texas coastline with the eight major bay study sites noted. Bay boundaries were adapted from the major bays shapefile provided by the Texas Parks and Wildlife Department, Coastal Fisheries Division.

**Table 1.** Environmental characteristics for each major bay, showing the variation of mean depth not including dredged channels, maximum depth including dredged channels, surface area, volume, average temperature, and average salinity. Depth (maximum and mean), surface area, and volume were obtained from the literature, state reports, and state nautical charts (adapted from Armstrong, 1987; Gonzales & Kinney, 2018). Temperature and salinity were calculated from the original data set as 10-year means ± SD (2014–2023) to represent the average temperature and salinity gradient observed across the coastline year-round.

| Major bay | Average depth (m) | Max depth dredged (m) | Surface area (ha) | Volume (km³) | Average temperature (C°) | Average salinity (‰) |
|---|---|---|---|---|---|---|
| Sabine Lake | 1.8 | 12.0 | 17,798 | 0.33 | 22.78 ± 6.87 | 7.04 ± 6.04 |
| Galveston Bay | 2.1 | 9.1 | 143,153 | 2.91 | 23.69 ± 6.73 | 16.85 ± 8.97 |
| Matagorda Bay | 2.3 | 13.7 | 101,368 | 2.13 | 24.01 ± 6.59 | 19.04 ± 8.55 |
| San Antonio Bay | 1.4 | 9.4 | 56,162 | 0.75 | 24.32 ± 6.49 | 21.58 ± 9.52 |
| Aransas Bay | 2.0 | 6.1 | 46,279 | 0.93 | 23.96 ± 6.62 | 20.26 ± 8.41 |
| Corpus Christi Bay | 2.4 | 13.7 | 44,451 | 1.15 | 24.1 ± 6.07 | 29.46 ± 5.77 |
| Laguna Madre | 1.1 | 3.7 | 214,545 | 2.57 | 25.45 ± 6.17 | 33.93 ± 9.19 |

The GPS coordinates are also recorded before the start of the sample on the shoreline where the seining starts. After seining for the 15.2-m distance, the seine is pulled onto the shoreline to begin identifying organisms with a greater than 5 mm total length to the lowest phylogenetic level possible. Fish captured by bag seines are generally 170–300 mm in total length, representing young of the year or juveniles of Red Drum, Spotted Seatrout, Black Drum, and Southern Flounder (Murphy & McMichael, 2002; Murphy & Taylor, 1989; Stunz et al., 2000; Wilson & Nieland, 1994).

## Data analysis

### *Data cleaning*

To assess changes in fish abundance over time and across bays, we converted catch data for each species in each bay to catch per unit effort (CPUE). We calculated CPUE as per unit of area, dividing catch (number of fish) by the area swept by the bag-seine net (in hectares). We examined monthly averages of each species' CPUE in each bay over 10 years (2014–2023) to assess seasonal patterns of peak recruitment windows in each bay (Figures S5–S8 [see online Supplementary Material]). Understanding the seasonal patterns of each species' peak recruitment into and out of juvenile habitats was essential to avoid misinterpreting CPUE fluctuations that resulted solely from cycles in juvenile presence from those driven by storm effects (Rooker et al., 1998). We established recruitment windows by plotting each species' monthly average CPUE by day of the year, with each year between 2014 and 2023 represented by a different color (Figures S5–S8). These visualizations allowed us to delineate the time windows within a calendar year where the postsettlement and juvenile stages of each species were the most abundant within the bays, which aligned with recruitment timing into nursery habitats previously established in the literature (Table 2; Rooker et al., 1998; Stokes, 1977; Stunz et al., 2002a, 2002b). Moving forward in our analysis, we only selected catch data for postevent responses from the established recruitment windows specific to each species.

### *Percent change analysis*

We used percent change analysis to understand how CPUE changed postevent for each species and bay to assess resistance and resilience. For each species, we first established a baseline of the average annual CPUE during the species' recruitment window for the 10 years before Hurricane Harvey (2007–2016) to represent prestorm values and the 10 years before the 2021 freeze (2010–2019) to represent prefreeze values. The 2021 freeze baseline avoids any period during the onset of the COVID-19 pandemic within the United States, as data collection was paused during quarantine measures. We chose a baseline of 10 years because management regulations of these species were relatively consistent over that timescale. For each species in each bay, we calculated the percent change for the first postevent year as the difference between the species' baseline average CPUE and the average CPUE in the first recruitment postevent window to measure resistance. We completed the same percent change calculation for the second recruitment postevent window to measure resilience. We accounted for interannual variation in the baseline CPUE by including the 25th to the 75th percentile of the year-to-year change. We defined resistance and resilience to an extreme event as the percent change in the first or second year postevent, respectively, remaining within or exceeding the interannual variation range for five or more bays (i.e., the majority of eight bays).

### *Time series analysis*

To complement our percent change analysis, we also examined catch over time (bag-seine count data from 2014 to 2023) using a generalized linear mixed model with a negative binomial distribution to account for overdispersion. We built the model using the glmer.nb() function from the lme4 package in R (Bates et al., 2015). There were four generalized linear mixed models for each storm event (one per species). We examined total species counts with the fixed effects of storm classification, year, and month as a combination of sine and cosine terms (to account for temporal autocorrelation). We included major bay regions as a random effect for each species for both storms. We defined storm classification as a variable in the model with three possibilities: "nonstorm," "storm," (the month of the storm) and "poststorm." The Black Drum and Southern Flounder models had one less storm classification level, as we removed the storm period classification for the freeze as both species had zero catches during the storm month. All model validation checks and assumptions were conducted, including assessments of the residual distribution, and can be found in the

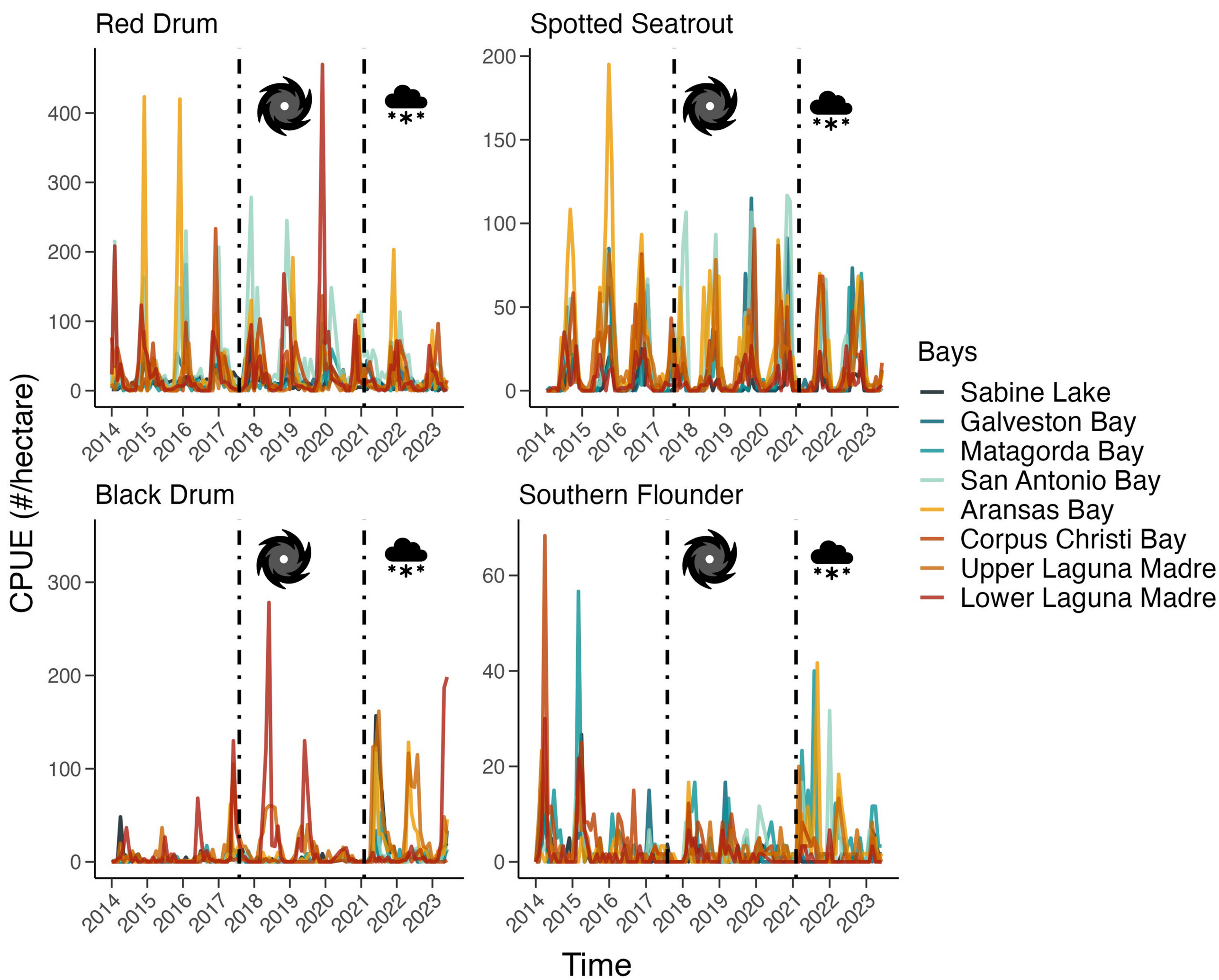


**Figure 2.** Time series depicting the seasonal variation of catch per unit effort (CPUE; number of individuals per hectare) over 10 years (2014–2023) by bay and species. Each bay is marked by a different color to show the strong seasonal trends of CPUE for each species, with each bay having its own unique seasonal pattern overlayed. The occurrence of Hurricane Harvey and the 2021 Texas freeze event are represented by vertical dotted lines and respective symbols.



**Table 2.** Relevant biological characteristics for each fish species, including their respective recruitment window from our analysis and typical spawning season found in the literature.

| Species | Recruitment window | Spawning season | Citation |
|---|---|---|---|
| **Red Drum** | October–May of the following year | Mid-August to mid-October | Rooker et al., 1998; Wilson & Nieland, 1994 |
| **Spotted Seatrout** | June–December | April–October | Murphy & McMichael, 2002; Rooker et al., 1998 |
| **Black Drum** | April–October | February–April | Nieland & Wilson, 1993 |
| **Southern Flounder** | February–July | November–December | Matlock, 1991; Stokes, 1977 |

online Supplemental Material. We performed all data cleaning and analyses in R version 3.1 (R Core Team, 2024).

## RESULTS

Over 10 years (2013–2023), 17,779 bag-seine observations (number of nets) caught 12,352 Red Drum, 7,009 Spotted Seatrout, 4,037 Black Drum, and 770 Southern Flounder. We identified the Red Drum CPUE peak recruitment window from the start of October through the end of May of the following year (Figure 2; Figures S1.1–S1.4). Spotted Seatrout's peak recruitment was delineated as the start of June through the end of December of the same year, Black Drum as April through the end of October of the same year, and Southern Flounder's as February through the end of July of the same year (Figure 2; Figures S5–S8).

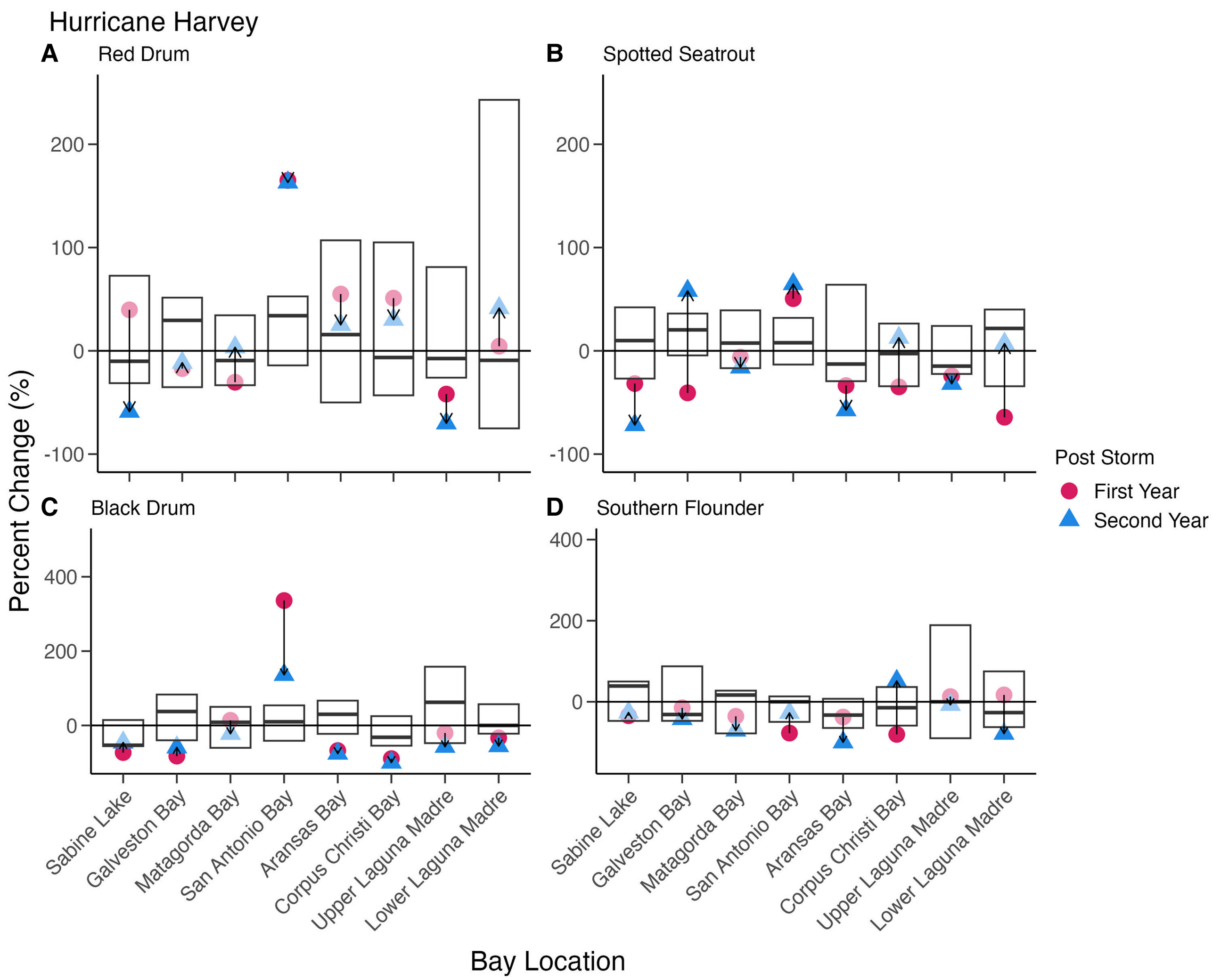


**Figure 3.** Percent change in the average catch per unit effort (CPUE) in the first and second years after Hurricane Harvey (red circles and blue triangles, respectively) compared with the baseline 10-year average CPUE before the hurricane for each fish species: (A) Red Drum, (B) Spotted Seatrout, (C) Black Drum, and (D) Southern Flounder. The boxes represent the 25th, 50th, and 75th percentile range of the average CPUE percent change within the 10-year baseline. Any value lower than the baseline and outside of this range (red circle or blue triangle fully solid) is denoted as a potential storm effect from the hurricane event.

### Red Drum

*Hurricane Harvey*

Red Drum met the threshold for species-level resistance after Hurricane Harvey, with resistance observed in Sabine Lake, Galveston Bay, Matagorda Bay, San Antonio Bay, Aransas Bay, Corpus Christi, and the lower Laguna Madre (Figure 3A; Table S1 [see online Supplementary Material]). We observed lack of resistance only in the upper Laguna Madre. Red Drum also met the threshold for species-level resilience after the hurricane, with resilience observed in six out of eight bays: Galveston Bay, Matagorda Bay, San Antonio Bay, Aransas Bay, Corpus Christi Bay, and the lower Laguna Madre (Figure 3A; Table S1). Lack of resilience was only observed in two out of eight bays, in Sabine Lake and the upper Laguna Madre (Figure 3A; Table S1). We found Red Drum exhibited a significant increase in juvenile abundance during the poststorm period following Hurricane Harvey, with a 32.2% increase in catch for the 2 years poststorm compared to nonstorm periods ($P < 0.001$). In contrast, juvenile counts during the storm month were not significantly different from nonstorm conditions ($P = 0.877$), suggesting that immediate storm impacts on juvenile Red Drum were minimal and observed increases occurred in the subsequent posthurricane period (Table S9).

*2021 freeze*

Responses to the 2021 freeze were different from the responses after Hurricane Harvey and also varied by species and major bay (Figures 4A and 5). Red Drum met the threshold for species-level resistance, with first-year percent changes exceeding the 10-year baseline in five of eight bays: Galveston Bay, San Antonio Bay, Aransas Bay, Corpus Christi Bay, and the upper Laguna Madre (Figure 4A; Table S5). We only found no resistance in Sabine Lake, Matagorda Bay, and the lower Laguna Madre, where first-year percent changes were lower than the 10-year baseline average of percent changes. (Figure 4A; Table S5). In contrast, Red Drum did not exhibit species-level resilience in the second year after the freeze, as percent changes

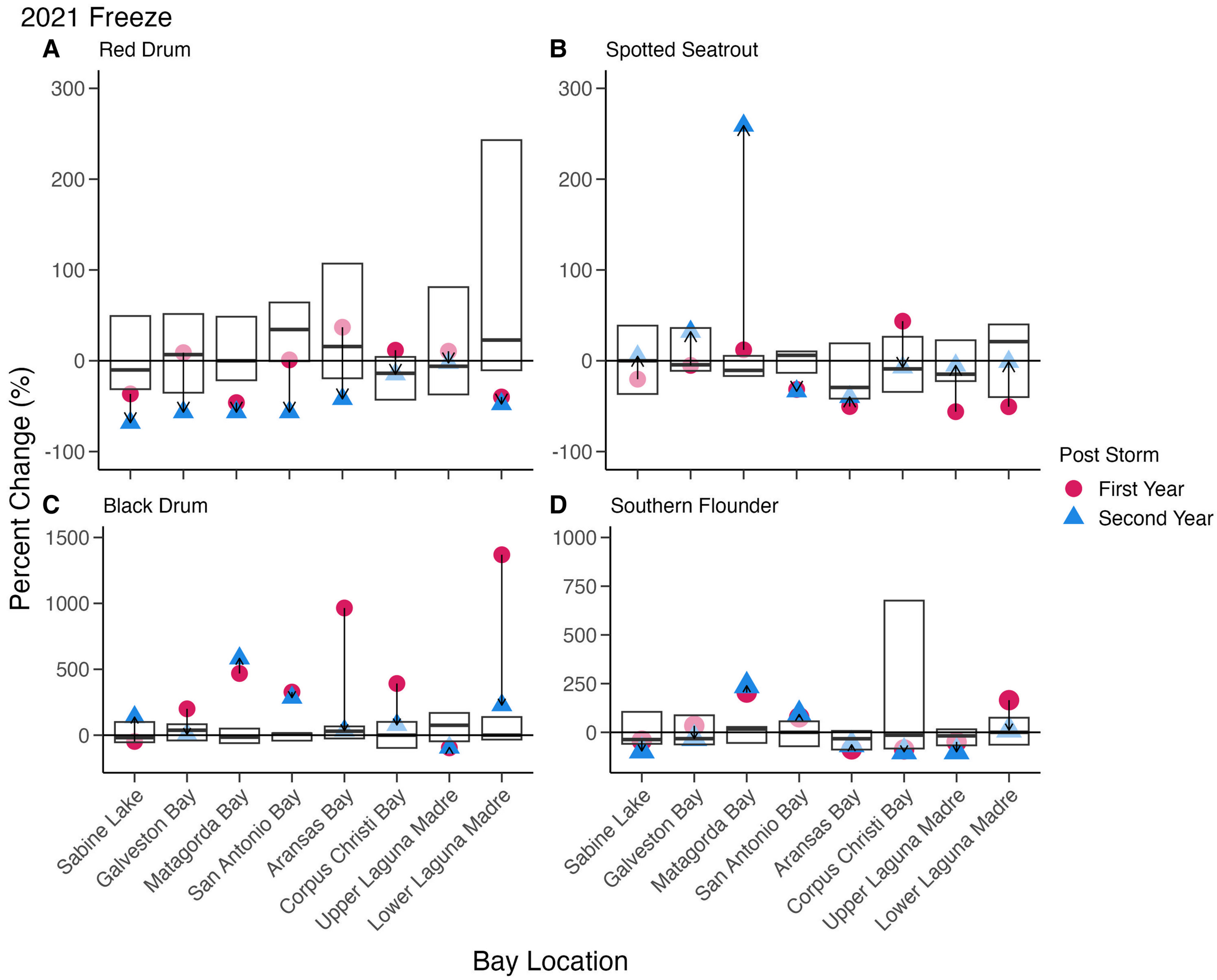


**Figure 4.** Percent change of the average catch per unit effort (CPUE) in the first and second years after the 2021 Texas freeze event (red circles and blue triangles, respectively) compared with the baseline 10-year average of CPUE before the 2021 freeze event for each fish species: (A) Red Drum, (B) Spotted Seatrout, (C) Black Drum, and (D) Southern Flounder. The boxes show the 25th, 50th, and 75th percentile range of the average CPUE percent change within the 10-year baseline. Any value lower than the baseline and outside of this range (red circle or blue triangle fully solid) is denoted as a potential storm effect from the 2021 freeze.

| Species | Hurricane Harvey | Texas Freeze |
|---|---|---|
| Red Drum | Resistance: Yes<br>Resilience: Yes | Resistance: Yes<br>Resilience: No |
| Spotted Seatrout | Resistance: No<br>Resilience: Yes | Resistance: No<br>Resilience: Yes |
| Black Drum | Resistance: No<br>Resilience: No | Resistance: Yes<br>Resilience: Yes |
| Southern Flounder | Resistance: Yes<br>Resilience: Yes | Resistance: Yes<br>Resilience: Yes |

**Figure 5.** A summary of species-level resistance and resilience by event. Observed resistance is the percent change in the first year poststorm remaining within the annual variation for at least five or more bays. Observed resilience is the percent change in the second year poststorm returning and/or remaining within the annual variation range for at least five or more bays. In each respective storm category, green denotes fish responses that were both resistant and resilient, yellow denotes either resistance or resilience was observed, and red denotes neither resistance nor resilient was observed.

remained below baseline levels in six out of eight bays: Sabine Lake, Galveston Bay, Matagorda Bay, San Antonio Bay, Aransas Bay, and the lower Laguna Madre. We observed resilience only in Corpus Christi Bay and the upper Laguna Madre during the 2-year mark. Additionally, Red Drum counts across the major bays significantly declined by 63.2% during the storm period associated with the 2021 Texas freeze ($P < 0.001$). A smaller but still significant decline of 16.1% was observed in the postfreeze period compared with nonstorm classifications ($P = 0.025$), providing further evidence of sustained impacts following the freeze (Table S13).

### Spotted Seatrout

#### *Hurricane Harvey*

Spotted Seatrout did not meet the threshold for species-level resistance after the hurricane. We observed a lack of resistance in six bays out of eight, including Sabine Lake, Galveston Bay, Aransas Bay, Corpus Christi Bay, upper Laguna Madre, and the lower Laguna Madre, with resistance only observed in Matagorda Bay and San Antonio Bay (Figure 3B; Table S2). However, Spotted Seatrout did meet the threshold for species-level resilience, which was observed in Galveston Bay, Matagorda Bay, San Antonio Bay, Corpus Christi Bay, and the lower Laguna Madre (Figure 3B; Table S2). We found a lack of resilience in Sabine Lake, Aransas Bay, and the upper Laguna Madre, only three out of the eight bays in the second year after the storm. From the generalized mixed model, Spotted Seatrout juvenile counts declined significantly during and after Hurricane Harvey. During the storm month, abundance decreased by 74.1% compared with nonstorm conditions ($P < 0.001$), indicating substantial immediate impacts. Poststorm periods were also associated with a 21.0% decline relative to baseline levels ($P = 0.0012$), suggesting that effects of the storm persisted into the 2-year period following Hurricane Harvey (Table S10).

#### *2021 freeze*

For Spotted Seatrout, we found a lack of resistance after the 2021 freeze in four out of the eight bays, San Antonio Bay, Aransas Bay, upper Laguna Madre, and lower Laguna Madre, but we did find resistance in Sabine Lake, Galveston Bay, Matagorda Bay, and Corpus Christi Bay (Figure 4B; Table S6). By the second year, Spotted Seatrout showed resilience in all bays except for San Antonio Bay, showing a substantial recovery in Aransas Bay and the Laguna Madre bay system (Figure 4B; Table S6). Spotted Seatrout counts across the bays during the storm period and poststorm period were found to be nonsignificant ($P = 0.543$ and 0.938, respectively), but our percent change analysis showed variable differences between bays, with the Laguna Madre system having steep declines while others, such as Corpus Christi and Matagorda Bay, had steep increases. This suggests the importance of analyzing species response spatially as well as temporally after extreme events such as the 2021 freeze (Table S14).

### Black Drum

#### *Hurricane Harvey*

Black Drum did not meet the criteria for species-level resistance after the hurricane, lacking resistance in five out of eight bays: Sabine Lake, Galveston Bay, Aransas Bay, Corpus Christi Bay, and the lower Laguna Madre. Black Drum also failed to meet the threshold for species-level resilience in five out of eight bays: Galveston Bay, Aransas Bay, Corpus Christi Bay, the upper Laguna Madre, and the lower Laguna Madre (Figure 3C; Table S3). Black Drum exhibited both resistance and resilience in the same two bays, in San Antonio Bay and Matagorda Bay (Figure 3C). From the generalized mixed model, neither storm nor poststorm classifications were significantly associated with changes in juvenile Black Drum counts compared with nonstorm conditions ($P = 0.683$ and 0.612, respectively; Table S11).

#### *2021 freeze*

We found that Black Drum exhibited resistance and resilience in seven out of eight bays, with a lack of resistance and resilience only observed in the upper Laguna Madre (Figure 4C; Table S7). Black Drum percent changes varied by bay but were only observed below the baseline threshold in the upper Laguna Madre for both the first and the second year after the storm. Black Drum was the only species to have this consistent storm response following the freeze and also such positive percent changes in the first year after the storm. Furthermore, we found Black Drum counts significantly increased by 81.2% during the poststorm period relative to nonstorm classifications ($P < 0.001$), indicating a strong positive response in the year following the Texas freeze (Table S15).

### Southern Flounder

#### *Hurricane Harvey*

We found evidence of both resistance and resilience for Southern Flounder. We observed resistance in six out of eight bays including Sabine Lake, Galveston Bay, Matagorda Bay, Aransas Bay, and the upper and lower Laguna Madre (Figure 3D; Table S4). We observed resilience for Southern Flounder in six slightly different bays out of the eight, including Sabine Lake, Galveston Bay, Matagorda Bay, San Antonio Bay, Corpus Christi Bay, and the upper Laguna Madre. Southern Flounder showed lack of resilience in only two out of eight bays, Aransas Bay and the lower Laguna Madre, while a lack of resistance was also found in only two bays, San Antonio Bay and Corpus Christi Bay (Figure 3D; Table S4). Southern Flounder juvenile catches declined significantly by 26.7% during the poststorm period relative to the nonstorm period ($P = 0.0036$), indicating a delayed response to Hurricane Harvey. While storm-month classifications were associated with a 67.0% decrease in counts, this effect was not statistically significant ($P = 0.159$; Table S12).

#### *2021 freeze*

Southern Flounder exhibited resistance in all bays except Aransas Bay after the freeze (Figure 4D; Table S8) and resilience in five out of the eight bays: Galveston Bay, Matagorda Bay, San Antonio Bay, Aransas Bay, and the lower Laguna Madre (Figure 4D; Table S8). Southern Flounder showed a lack resilience in the remaining three of eight bays: Sabine Lake, Corpus Christi Bay, and the upper Laguna Madre (Figure 4D; Table S8). Additionally, Southern Flounder counts increased significantly by 178.1% during the poststorm period compared with nonstorm periods ($P < 0.001$; Table S16).

### *Spatial patterns of resistance and resilience across bays*

Patterns of resistance and resilience varied spatially across species following both Hurricane Harvey and the 2021 freeze, though not always in accordance with environmental gradients such as depth, salinity, or temperature. Some bays consistently lacked resistance, resilience, or both for multiple species. For example, the upper Laguna Madre showed no resistance for Red Drum and Spotted Seatrout after Hurricane Harvey, and Black Drum also lacked resilience in the upper Laguna Madre in the freeze—notably the only bay to have lack of resilience during the freeze (Figures 3A–C and 4C; Tables S1–S3, S7). Similarly, after the 2021 freeze, Red Drum and Spotted Seatrout lacked both resistance and resilience in Sabine Lake, while Black Drum only lacked resistance in that bay. Notably, Red Drum exhibited more negative second-year percent change values in northern bays—Sabine Lake, Galveston Bay, and Matagorda Bay—compared with more stable or positive responses in southern bays like Corpus Christi Bay and the upper and lower Laguna Madre, which differ significantly in depth and salinity (Figure 4A; Table S5). Additionally, Corpus Christi Bay demonstrated resistance and resilience for three out of the four species (Red Drum, Spotted Seatrout, and Black Drum) following the freeze, possibly indicating the use of its deeper waters as a thermal refuge (Figure 4A–C; Tables S5–S7).

## DISCUSSION

Extreme events, like hurricanes and freezes, can negatively impact fish populations within coastal environments, ranging from declines in abundance to changes in relative body condition and habitat destruction (Adams et al., 2012; Bailey & van de Pol, 2016; Jentsch et al., 2007; Matich et al., 2020; Maxwell et al., 2019; Perret et al., 2010; Santos et al., 2016; Ummenhofer & Meehl, 2017). After Hurricane Harvey, two out of four species exhibited species-level resistance (Red Drum and Southern Flounder) and three exhibited species-level resilience (Red Drum, Spotted Seatrout, and Southern Flounder). The 2021 freeze elicited different species-specific responses compared with Hurricane Harvey. After the 2021 freeze, three of the four species exhibited species-level resistance (Red Drum, Black Drum, and Southern Flounder) and three out of four species exhibited species-level resilience (Spotted Seatrout, Black Drum, and Southern Flounder). The duration and cold temperatures of the 2021 freeze had not occurred on the Texas Gulf Coast since the 1980s (McEachron et al., 1994). Such an event may have influenced these study species differently, either because of direct mortality or the ability to escape to thermal refuges. Some estuarine fish species move to deeper, warmer water during rapid drops in water temperatures during freeze events to avoid direct mortality (Ellis et al., 2017; Gunter, 1951; Moulton et al., 2017; Stevens et al., 2016). We also observed variation in resistance and resilience across the bay systems and extreme events but with no apparent pattern to the environmental gradients known along the coastline, such as temperature and salinity.

### Red Drum

We found evidence for Red Drum resistance and resilience following Hurricane Harvey, with increases and nonsignificant declines in abundances across the majority of bays. Our results agree with previous research, as adult Red Drum can endure varying salinity levels after hurricanes and continue to experience successful spawning seasons 1 and/or 2 years after a hurricane, avoiding mass mortality or population declines (Pettis, 2018; Trenberth et al., 2018; van Oldenborgh et al., 2017). Adult Red Drum have been reported in salinities ranging from 0.8‰ to 45‰ (Crocker et al., 1981; Perret et al., 1980), highlighting their physiological tolerances to substantial salinity fluctuations. Additionally, prior research found no significant declines in age-0 Red Drum and Spotted Seatrout abundance in Powderhorn Lake—an estuary connected to Matagorda Bay—following Hurricane Harvey (Matich et al., 2020), further supporting the resiliency juvenile Red Drum have to withstand rapid salinity changes. Our findings also indicate an increase in abundance in the posthurricane period of Red Drum, possibly due to the decrease in fishing pressure immediately following the storm. Previous research has similarly demonstrated that hurricanes can temporarily reduce recreational fishing pressure by curtailing human activity, causing an increase of predator fish abundance, like Red Drum (Reustle et al., 2024). Following the 2021 freeze, we initially found that Red Drum showed resistance, likely due to their mobility between bays and ability to seek thermal refuge in deeper waters in adjacent bays. However, we observed a lack of resilience in the second year after the freeze, suggesting latent effects on juvenile recruitment. Red Drum have a minimum temperature tolerance of about 2–5°C, where severe winters can cause high mortality in juveniles, but Red Drum are more mobile compared with the other three species (Anderson & Scharf, 2014; Dance & Rooker, 2015, 2016; Moulton et al., 2017) Juveniles and subadults also move to deeper water to escape temperature extremes (Matlock, 1990; Matlock et al., 1978). The ability to move to thermal refuges may have aided the survival of Red Drum adults to a successful spawning season in the fall of 2021, as observed by resistance in the first year after the freeze. However, there may have been delayed effects on subsequent spawning and juvenile classes, as we found a lack of resilience in the second year. This lagged decline of juvenile Red Drum may have been due to low temperatures limiting growth or decreasing feeding rates during a critical life history stage for juveniles (Anderson & Scharf, 2014; Dance & Rooker, 2016).

### Spotted Seatrout

Spotted Seatrout inhabit similar environments as Red Drum, ranging from brackish to hypersaline (Holt & Holt, 2003). However, in contrast to Red Drum, we found that juvenile Spotted Seatrout exhibited a lack of resistance after Hurricane Harvey, with significant declines during the storm period and declines in percent change in six of eight bays. Our findings contrast with prior work done by Matich et al. (2020), which found no significant declines in juvenile Spotted Seatrout abundance after Hurricane Harvey in Powderhorn Lake. Our study reveals that significant declines did occur elsewhere, highlighting the importance of localized factors—such as bay morphology and connectivity—in shaping bay-specific responses to extreme events (Armstrong, 1987).

The February 2021 freeze had a more severe impact on Spotted Seatrout than Hurricane Harvey, particularly in the upper and lower Laguna Madre—shallow bays with limited deepwater thermal refuges and limited hydrological connectivity. Juvenile and adult Spotted Seatrout's abundance declines and lack of resistance observed in the first year may have been explained by the observed recruitment declines compared with the 10-year baseline average (Anweiler et al., 2014; Armstrong, 1987; Ellis et al., 2017; Fisk, 1959). Spotted Seatrout's largest declines occurred in the southern bays, where Spotted Seatrout juveniles may be locally adapted to warmer water conditions (Anweiler et al., 2014; Bortone, 2002; Ellis et al., 2017). Further, Spotted Seatrout (both juveniles and adults) exhibit high site fidelity, rarely leaving their natal estuaries (Baker & Matlock, 1993), which likely limited their ability to escape extreme cold temperatures. By the second year after the freeze, juvenile Spotted Seatrout CPUE values in most bays returned within defined resilience thresholds, potentially aided by prompt changes to recreational fishery regulations.

In response to the large declines in juvenile Spotted Seatrout CPUE in the Laguna Madre region, TPWD implemented an emergency change to the recreational harvest regulations to support recovery (TPWD News, 2021b). Spotted Seatrout individuals can concentrate in thermal refuges during rapid declines in water temperature (Ellis et al., 2017), elevating catchability by anglers and risking overharvest. These management actions reflected lessons from prior freeze events in the Texas Gulf Coast in 1983 and 1989 and in Florida in 2010, where similar abundance declines were followed by multiyear recoveries (McEachron et al., 1994; Santos et al., 2016; Stevens et al., 2016). However, 1 year of stronger recruitment is not enough to replenish the size and age structure of the adult populations, reflected in subsequent TPWD gill-net data that still reported declines in fall of 2023 (Bonnot, 2023; TPWD News, 2021a). In response, TWPD adopted a permanent, statewide harvest regulation change for Spotted Seatrout effective March 26, 2024, to continue to support its long-term recovery. Given Spotted Seatrout's estuarine dependence, high site fidelity, and observed spatial variability in storm responses, long-term recovery and resilience may require further place-based management strategies. Regional differences in growth and mortality rates along the Texas Gulf Coast (Anderson et al., 2022) further underscore the importance of bay-level approaches to recreational harvest regulations and fishery management under increasing climate instability.

### Black Drum

Despite being a euryhaline species like the other fishes in this study, we observed a lack of resistance and resilience after Hurricane Harvey for Black Drum, with lower juvenile abundances captured in both the first and second years. However, these declines in hurricane and posthurricane periods were not statistically significant. Black Drum are known for their tolerance of extreme environmental conditions and broad salinity ranges as demonstrated by their prevalence in hypersaline habitats such as the Laguna Madre system (Olsen, 2014) and low-salinity areas of Galveston Bay (Livernois et al., 2021). Therefore, observed nonsignificant poststorm declines may not be due to direct mortality or immediate storm impacts but reduced body condition. For example, larvae produced by fish in poorer body conditions (i.e., decreases in length and/or weight) have been linked to reduced survival to juvenile stages (Marteinsdottir & Begg, 2002; Marteinsdottir & Steinarsson, 1998). In other studies, Matich et al. (2020) found no statistically significant declines in abundance but did find negative changes to the relative body condition of age-0 Red Drum and Spotted Seatrout after Hurricane Harvey. A similar phenomenon may have occurred for Black Drum (and potentially other study species) after Hurricane Harvey, as the fishes we studied can differ in energetic costs for osmoregulation in lower salinities and the effects are not apparent in abundance trends alone (Holt & Holt, 2003; Wohlschlag & Wakeman, 1978). Additionally, in 2012, an emaciation event among Black Drum in Baffin Bay was attributed to reduced prey availability caused by salinity changes (Olsen, 2016; Olsen et al., 2014), and subsequent telemetry studies documented increased adult movements at low salinities (Ajemian et al., 2018). Our findings may encourage further research into the hypothesis that adult dispersal following Hurricane Harvey may have influenced juvenile distributions, contributing to observed "declines" in catch data.

In contrast to Hurricane Harvey, we found that Black Drum showed a significant increase in juvenile abundance in freeze and postfreeze periods. Black Drum are capable of moving to deeper waters to avoid freezing temperatures (Simmons & Breuer, 1962), which may have facilitated their postfreeze resilience and increased abundance. Additionally, decreased fishing pressure—previously observed following hurricanes—can lead to increases in predator fish populations (e.g., Black Drum) (Reustle et al., 2024). While Reustle et al. (2024) focused on hurricane impacts to decreased fishing pressure, similar mechanisms may be relevant to other types of extreme events, such as winter storms. The contrasting response patterns of Black Drum to hurricanes versus freezes highlight the importance of incorporating multiple types of extreme events into ecological studies and reinforces the need to better understand the mechanisms driving species-specific responses to different acute environmental stressors.

### Southern Flounder

Southern Flounder exhibited resistance and resilience following Hurricane Harvey as defined by our percent change thresholds; however, we also observed statistically significant decreases in catch rates during the poststorm period. While Southern Flounder is a euryhaline species, capable of surviving wide salinity fluctuations, including successful acclimation of juveniles from 10‰ to 0‰ in past experimental conditions (Smith et al., 1999), the species has also experienced long-term population declines due to overharvesting in the recreational fishery (Froeschke et al., 2011). These declines have prompted recovery efforts by TPWD, such as seasonal closures and bag limit changes, making it difficult to disentangle the direct effects of storm events from broader population trends in catch data.

Despite this complexity, Southern Flounder showed increasing postfreeze catches following the 2021 Texas freeze. This response may be due to their capacity to migrate away from rapidly freezing water temperatures and their broad thermal tolerances (McDonald et al., 2016; Stokes, 1977; Taylor et al., 2000). Similar to Black Drum and Red Drum, Southern Flounder may have benefitted from temporary reductions in fishing pressure or favorable poststorm environmental conditions.

### Spatial patterns

Spatial patterns of resistance and resilience following Hurricane Harvey and the 2021 freeze did not consistently align with expectations based on Texas's environmental gradients. We hypothesized that spatial variation in responses would reflect thermal and salinity gradients, along with other factors such as proximity to Hurricane Harvey's landfall and access to deeper water during the freeze (e.g., deeper Corpus Christi Bay versus shallow Laguna Madre). Similar spatial variability has been reported in other systems (Stevens et al., 2016) where estuary-specific responses to a cold snap were attributed to differences in bay geomorphology, temperature, salinity, and latitude.

For example, Red Drum showed greater declines in northern bays following the freeze, contrary to our hypothesis. For Southern Flounder, previous studies have suggested that high salinity may mitigate cold temperature stress (Taylor et al., 2000); however, we did not observe consistent bay-specific patterns of resistance or resilience that aligned with salinity gradients. Conversely, the pattern shown by Spotted Seatrout aligned with our expectations. In the southern Laguna Madre system, Spotted Seatrout accounted for 89% of the species' total kill TPWD gill-net data (TPWD News, 2021b). This pattern was mirrored in our bag-seine data analysis, showing steep declines in shallow upper and lower Laguna Madre, likely due to limited access to deeper water. Although individual species' responses among bays did not appear to follow any specific pattern concerning the environmental gradients, this may reflect the complex interactions of ecological and physical factors rather than an absence of spatial structure. Future research could apply more spatially explicit approaches, such as predictive modeling techniques (Patrick et al., 2022) or acoustic telemetry studies designed when expecting an extreme event (Gutowsky et al., 2021). Research to identify the drivers of interbay variability will improve our understanding of how extreme events shape coastal ecosystems and support more refined, placed-based management strategies for recreational fisheries.

### Limitations and future work

A limitation of our study is the relatively short time since the 2021 freeze, which limited the length of our postevent analysis. Having sufficient postevent time is particularly important in evaluating how each fish species' recruitment trends and juvenile abundances translate to the adult population, and future studies could continue a longer time series analysis. Additionally, the inherent variability in juvenile recruitment, partly influenced by the high fecundity of some of the study species, can present challenges when interpreting short-term population changes (Winemiller & Rose, 1992). To attempt to address this differently, we compared recruitment windows during defined postevent periods to isolate event-specific cohort responses and reduce the confounding effects of high fecundity, which can obscure population-level impacts of extreme events. Resilient juvenile abundances for these fish species are a hopeful sign towards improved adult populations and overall population stability, but we also need an improved understanding of how juvenile resiliency translates to adult populations. Thus, future work could examine and compare different rates of resistance or resilience at distinct life history stages after extreme events. Resistance and resilience, on their own, may not adequately capture fish responses as other traits, like relative body condition, may have also been altered. Expanding analysis beyond single-event case studies could improve our ability to generalize species responses to various stressors. Lastly, incorporating recreational fisheries within a broader socioecological framework, including adaptive management responses to extreme events, could further enhance our understanding of coastal ecosystem dynamics (White & Wulfing, 2024).

Our study also enhances our understanding of how estuarine fish species respond to hurricanes and cold snaps while providing recommendations for place-based management strategies to combat adverse effects on fine spatial and temporal scales. Our results provide additional evidence of freeze events and rapid environmental change negatively affecting estuarine fish, especially those with limited movement behaviors and lower cold temperature limits like the Spotted Seatrout. In addition, we demonstrate the importance of long-term monitoring programs establishing baseline data, such as TPWD's fishery-independent surveys, to mitigate future threats to coastal ecosystems (Dance & Rooker, 2016; Froeschke & Froeschke, 2011; Furey & Rooker, 2013; Livernois et al., 2021). Finally, our study suggests that future research in extreme event ecology can enhance management strategies for population recovery, particularly in a changing climate (Bailey & van de Pol, 2016).

## SUPPLEMENTARY MATERIAL

Supplementary material is available at *Marine and Coastal Fisheries* online.

## DATA AVAILABILITY

All data were provided by TPWD Coastal Fisheries Division. All code for data analysis is available at https://github.com/anasilverio19/TXExtremeEvents_Pub. The data set used for this project can be requested from Dr. Mark Fisher, the science director at TPWD at mark.fisher@tpwd.texas.gov. Spatial data used for bay boundaries were obtained from TPWD Coastal Fisheries GIS Lab (MajorBays shapefile; credit: Ashley Summers, GIS analyst). Data are publicly available upon request from TPWD.

## ETHICS STATEMENT

This study followed the ethical guidelines for publication outlined by the American Fisheries Society.

## FUNDING

The project was partially supported by the University of New Hampshire through a Summer Teaching Assistant Fellowship awarded by the graduate school in the summer of 2023. Preparation of this manuscript was funded in part by award #NA25OARX417C0142-T1-01 to New Hampshire Sea Grant from the National Oceanic and Atmospheric Administration's National Sea Grant College Program, U.S. Department of Commerce.

## CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

## ACKNOWLEDGMENTS

Ana Silverio was partially supported by a University of New Hampshire Summer Teaching Assistant Fellowship awarded by the University of New Hampshire Graduate School. We thank the TPWD and Dr. Mark Fisher for providing the data and guidance throughout the project. We also thank the TPWD Coastal Fisheries Division, the field sampling staff for collecting the data, and the data management staff for compiling it. Additionally, we thank Dr. Nathan Furey and the Quantitative Marine Ecology Lab at the University of New Hampshire for their guidance and support during this project. The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of New Hampshire Sea Grant, the National Oceanic and Atmospheric Administration's National Sea Grant College Program, or the U.S. Department of Commerce.

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