



Spatiotemporal Patterns of Gars in Two Subtropical Estuaries

Anna N. DeMotte^{1,2} · Emily N. Meese^{1,3} · Carey G. Gelpi⁴ · Christine C. Jensen⁵ · R. J. David Wells^{1,6}

Received: 8 May 2026 / Revised: 18 September 2026 / Accepted: 21 September 2026
© The Author(s) 2026

Abstract

Characterizing drivers of estuarine fish assemblages provides valuable insights into estuarine ecology and how each species may react to stressors such as climate change and anthropogenic disturbances. Although they are known to inhabit estuaries, gars are managed as freshwater species and little is known about their movements, reproduction, or other ecological requirements. This study quantitatively describes and compares spatiotemporal dynamics of Alligator Gar (*Atractosteus spatula*), Spotted Gar (*Lepisosteus oculatus*), and Longnose Gar (*Lepisosteus osseus*) in two subtropical estuaries in the northwestern Gulf of Mexico. Thirty-three years of data from a long-term monitoring program were used in hurdle models to identify abiotic factors that impacted gar presence and abundance and to map spatial hot spots to find spatiotemporal patterns within the species assemblage. Within both Galveston Bay and Sabine Lake, season and salinity were the primary drivers of gar presence and abundance for all three species. Alligator Gar were more abundant in higher salinity areas than Spotted Gar and Longnose Gar. Longnose Gar were most abundant in areas with the lowest salinity. All species were most abundant in the spring on the eastern side of both estuaries, correlating strongly with the spring spawning season and marshes and tidal creeks that are less anthropogenically disturbed and frequently flooded. The results of this study suggest potential niche partitioning through species-specific salinity thresholds and the importance of undisturbed marsh habitat and tidal creeks.

Keywords Species assemblages · Estuarine ecology · Fisheries management · Galveston Bay · Sabine Lake

Introduction

Estuaries provide important habitats for a wide range of fish life stages, either for obligate or facultative use (Able, 2005; Barletta et al., 2005). They provide nursery grounds, shelter, and food resources, which shape population and community level ecological processes (Able, 2005; Mosman et al., 2023; Whitfield, 2021). Estuaries are also highly dynamic in nature, experiencing multiscale environmental changes (e.g., season, tides, wind) and anthropogenic influences (e.g., shipping channels, material processing plants, agricultural runoff), requiring resident and migratory species to adapt to environmental fluctuations (Hu et al., 2023; Ogbodo et al., 2024; Whitfield, 2021).

A suite of species navigates the challenges associated with estuarine environments, and gars are increasingly of interest to fisheries managers and researchers (Bartnicki et al., 2021; Daugherty et al., 2018; Lackmann et al., 2024; Marsaly et al., 2023; Smith et al., 2018, 2020). There are five extant species of gars in the United States, three of which have overlapping distributions in the riverine and

Communicated by James Allen Nelson

✉ Anna N. DeMotte
anna.demotte@gmail.com; andemotte@vims.edu

¹ Department of Marine Biology, College of Marine Sciences and Maritime Studies, Texas A&M University, Galveston, TX 77553, USA

² Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, VA 23062, USA

³ Marine Science Institute, University of California Santa Barbara, Santa Barbara, CA 93111, USA

⁴ Coastal Fisheries Division, Texas Parks and Wildlife Department, Port Arthur, TX 77640, USA

⁵ Coastal Fisheries Division, Texas Parks and Wildlife Department, Dickinson, TX 77539, USA

⁶ Department of Ecology and Conservation Biology, Texas A&M University, College Station, TX 77843, USA

estuarine habitats of the northern Gulf of Mexico: Alligator Gar (*Atractosteus spatula*), Spotted Gar (*Lepisosteus oculatus*), and Longnose Gar (*Lepisosteus osseus*) (Ferarra, 2001). Despite knowledge that some populations use both river and estuarine habitats, sometimes traversing between the two areas, gars in the northern Gulf of Mexico are managed on a broad state level as a freshwater species (Bohn et al., 2023; Buckmeier et al., 2013; Daugherty et al., 2017; Livernois et al., 2021; Love, 2004; McAllister et al., 2022; O'Connell et al., 2007; Schwartz, 2003; Smylie et al., 2016). Populations with home ranges spanning across rivers and estuaries may link freshwater and marine food webs through habitat coupling dynamics (Livernois et al., 2024; Sheaves et al., 2013; St. George et al., 2023). Their use of both freshwater and saltwater habitats highlights their adaptability and underscores the need to better understand what drives their spatiotemporal presence and abundance.

Identifying patterns of species distribution and species assemblages is a critical component of community ecology as various environmental and anthropogenic factors influence species populations over space and time (Bacheler et al., 2009; Barletta et al., 2005; Bi et al., 2021; Fernandes et al., 2014; Fontaine et al., 2024; Gonzalez et al., 2021; Matich et al., 2017). Species assemblages, defined as groups of species occurring in a particular area with common environmental preferences, provide valuable insights into community relationships, habitat use, and ecological mechanisms like competition and resource partitioning (Amundsen et al., 2003; Kleisner et al., 2016; Livernois et al., 2024). For gars, abiotic factors like salinity, temperature, dissolved oxygen, and turbidity as well as flooding magnitude and inundation period are known to influence various ontogenetic processes and behaviors (Bartnicki et al., 2021; Gray et al., 2012; Long et al., 2020; Martínez et al., 2021). Identifying abiotic factors that drive spatiotemporal patterns of gar species assemblages in estuaries is essential for understanding community ecology dynamics as well as developing tailored management strategies.

This study uses 33 years of fishery-independent long-term monitoring data (1986–2018) to investigate gar species assemblages and spatiotemporal distribution in two major estuarine systems along the northern Gulf of Mexico. Specifically, this study seeks to describe the estuarine- and species-specific environmental niche that gars inhabit by investigating how abiotic factors influence gar presence and abundance in estuarine habitat and if those patterns are similar between two estuaries. Monitoring both the abundance of gars and environmental parameters in an estuary provides managers with baseline and long-term trend information that help elucidate the effects of environmental change, evaluate the effectiveness of management actions, and make informed, adaptive decisions that support sustainable fisheries and ecosystem health.

Methods

Study Area

This study examines historical data from two major estuarine systems in the northern Gulf of Mexico: Galveston Bay and Sabine Lake (Fig. 1a). Galveston Bay is the larger of the two at approximately 387,000 acres (TPWD ArcGIS Open Data) and is fully encompassed within Texas state borders (Fig. 1b) (Stukey et al., 2004). Saltwater from the Gulf of Mexico enters in the southern part of Galveston Bay through San Luis Pass, the Bolivar Roads section of the Houston Ship Channel, and historically, Rollover Pass (opened in 1955 and closed in 2019) (Gonzalez et al., 2021; Watson, 1999). Freshwater enters in the northern part of the estuary through both the Trinity River and the San Jacinto River. Studies in Galveston Bay commonly distinguish five ecologically distinct areas differentiated by salinity dynamics and available habitat types: the Trinity Bay Area, Upper Galveston Bay Area (UG Bay in Fig. 1b), East Bay Area, Lower Galveston Bay Area (LG Bay in Fig. 1b), and West Bay Area (Fig. 1b) (Livernois et al., 2021; Steichen & Quigg, 2018). The Trinity Bay Area is in the northeast corner of Galveston Bay, between the confluence of the San Jacinto River and East Bay. It includes the confluence of the Trinity River and salt marsh area. Both the Upper Galveston Bay and Lower Galveston Bay areas are highly developed on the western sides due to the expansion of the Greater Houston metropolitan area. The East Bay Area is surrounded by the Bolivar Peninsula, a barrier island where Rollover Pass was located, and the West Bay Area spans the area west of Lower Galveston Bay. This area is less developed and receives saltwater influx from San Luis Pass.

Sabine Lake is a smaller estuary at approximately 72,000 acres (TPWD ArcGIS Open Data), located northeast of Galveston Bay and is divided by the Texas-Louisiana state line through the middle of the Sabine River in the north and continuing south through Sabine Pass in the south (Fig. 1c) (Stukey et al., 2004). Sabine Pass serves as the sole opening to the Gulf of Mexico, allowing saltwater to enter the estuary. Major sources of freshwater to the system include the Sabine River and Neches River located in the northern part of the estuary. There are several ecologically distinct areas in Sabine Lake, but for the purposes of this study, groupings are distinguished by the same characteristics listed for Galveston Bay: Lake Area, Salt Bayou Area, and Sabine Pass Area (Fig. 1c). The Lake Area encompasses the Neches and Sabine rivers and Sabine Lake itself. Bessie Heights, a remnant brackish marsh located on the Neches River just north of the confluence into Sabine Lake, is included in this area (Fig. 1c). The east side of the Lake Area is a marsh region with many bayou distributaries, which borders the

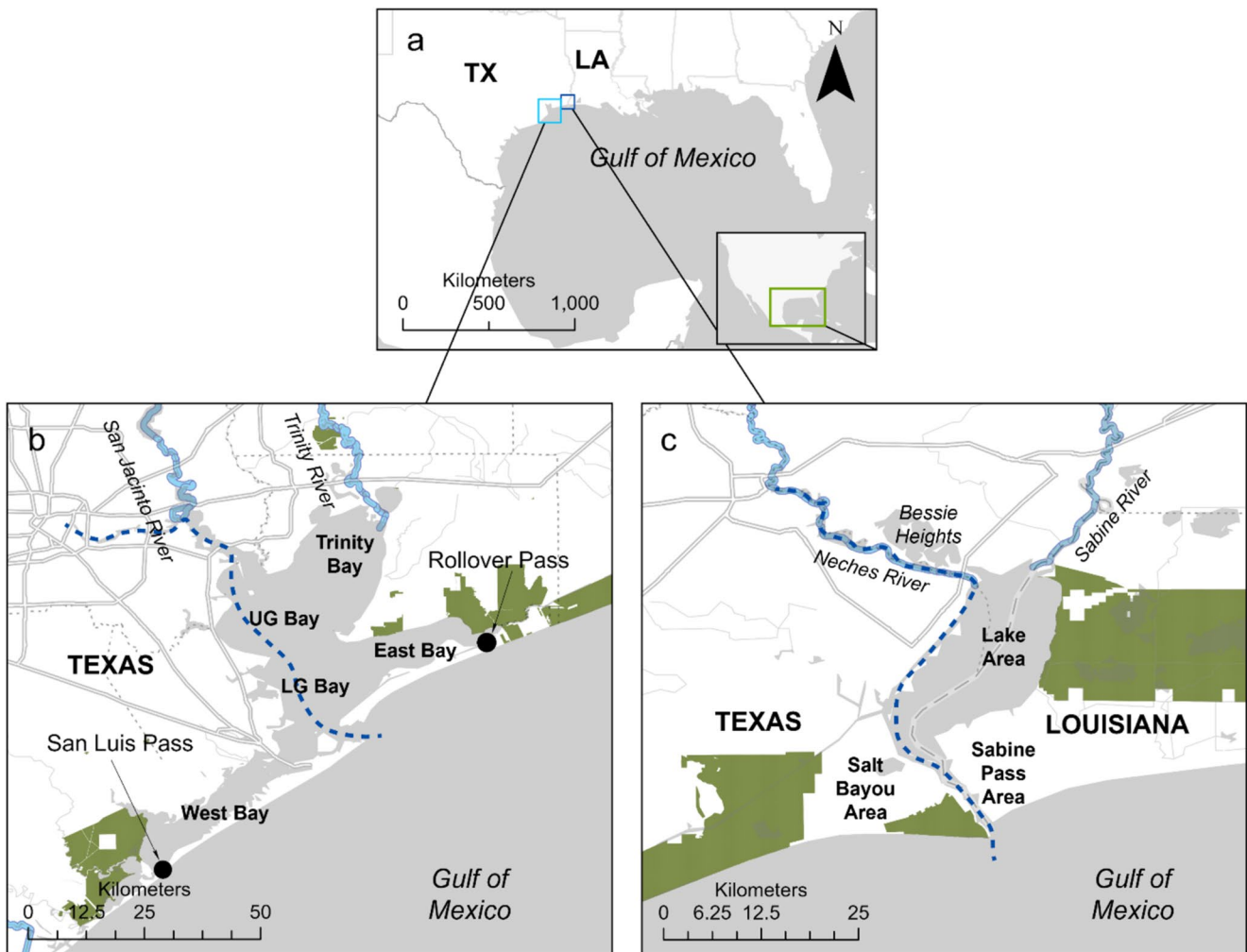


Fig. 1 Study area in the northern Gulf of Mexico (**a**) comprised of Galveston Bay (**b**) and Sabine Lake (**c**). Subareas of each estuary are labeled, as well as rivers (light blue), National Wildlife Refuges (green), and key features. An additional point of interest, Bessie

Heights, is also marked. The dotted line in (**b**) represents the Houston Ship Channel, and the dotted line in (**c**) represents the Sabine-Neches Waterway

Louisiana side of Sabine Lake (Fig. 1c). The Texas side of Sabine Lake is bordered by Pleasure Island, a dredge spoil island hardened by limestone, which has been developed for residential and commercial use and future dredge spoil retention. Salt Bayou Area encompasses the salt marsh area South of Port Arthur, between Sabine Pass and the Galveston Bay ecosystem.

Data Source

Data was collected from the Texas Parks and Wildlife Department (TPWD) Coastal Fisheries Division's Marine Resource Monitoring Program, an ongoing long-term fishery-independent program that consistently samples each major bay system along the Texas coast (Martinez-Andrade, 2018). The program began in 1975 using a variety of gear types, including gill nets, and methods were standardized

across all bays in 1986. Although multiple gear types were used, this study focused on gill-net catch data and associated abiotic variables from Galveston Bay and Sabine Lake (1986–2018) because gill nets effectively capture fish sizes appropriate for gars and the study goals.

Sample sites were randomly selected from grid maps using a stratified cluster sampling design (Martinez-Andrade, 2018). Sample grids are one-minute latitude by one-minute longitude and overlap sampleable shoreline. Each grid is further divided into 144 smaller gridlets that are five seconds latitude by five seconds longitude and overlap the shoreline. Gill nets are set overnight, and sampling occurs in both the spring and fall for 10 weeks each. The spring season begins the second full week of April, and the fall season begins the second full week of September. A total of 45 nets are set in each season ($n=90$ per year) in each bay system.

Gill nets used by TPWD are 182.9 m long, spread approximately 1.2 m vertically in the water column, and are composed of four panels of increasing mesh size (76 mm, 102 mm, 127 mm, 152 mm). Nets are deployed perpendicular to shore, with the smallest mesh size closest to the shore. Geographical coordinates are recorded with a global positioning system on the water's edge at the beginning of deployment. For each species caught in each mesh size per day, up to 19 individuals are measured to the nearest millimeter (mm) in total length (TL), and every additional individual afterwards is counted. Abiotic data is collected with a meter that measures salinity (ppt), temperature (°C), and dissolved oxygen (ppm). Water samples are retained in 60 mL bottles and transferred to 30 mL vials for turbidity level (NTU) analysis via a turbidimeter.

Data Analysis

Abiotic Modeling

Abiotic factors contributing to gar presence and abundance were modeled for each estuary, comparing data when gars were present and absent in the gill nets. Since gill-net catch data was highly zero-inflated (i.e., zero gar caught in a gill net), zero-inflated spatial “hurdle” models were conducted to elucidate which abiotic factors influenced gar presence and gar abundance (Bouyer et al., 2015; Cameron & Trivedi, 2003; Lewin et al., 2010; Steel et al., 2013). Hurdle models operate by (1) fitting a binomial model to model presence, (2) fitting a negative binomial model on the non-zero data to model abundance, then (3) combining the most parsimonious binomial and negative binomial models into one final model using the *glmmTMB* package in R (Brooks et al., 2017). A spatial component, incorporated by utilizing minor bay information provided in the TPWD data, was added to the model as a random effect to absorb spatial autocorrelation. Backwards stepwise regression was employed after assessing variables for collinearity via variance inflation factors and to remove non-significant variables, and model fit was assessed using the Akaike Information Criterion (AIC) (Lewin et al., 2010). Hurdle models were conducted separately for each estuary and species combination to interpret which abiotic factors led to higher numbers of gars present in any given area.

Inverse distance weighted (IDW) interpolation maps were created for each abiotic variable in each estuary and season to visualize seasonal dynamics in both estuaries. Abiotic factors were statistically compared between estuary and season via Kruskal-Wallis nonparametric tests and differences were assessed with Dunn post-hoc pairwise group comparisons. The IDW maps were qualitatively compared to spatial hot spot analyses to interpret ecological patterns.

Spatial Modeling

Spatial hot spot analyses were conducted to assess the spatial patterns of presence and abundance of gars within the estuaries. Hot spot analyses evaluate where data clusters in a geographic area, identifying statistically significant patterns of presence or absence in relation to neighboring data. In this case, hot spot analyses were used to examine the number of fish collected in a gill net compared to neighboring net catches, identifying data clusters in the estuaries with statistically high (hot spot) and statistically low (cold spot) numbers of gars. Hot spot (Getis-Ord Gi*) analyses were performed in ArcGIS with spatial autocorrelation (using the Global Moran's I tool) to find geographical distributions of each gar species (Betty et al., 2020; Catchpole et al., 2019; Stevens et al., 2022). Global Moran's I identified spatial relationships, pinpointing optimum distance thresholds which were fed to Getis-Ord Gi* as fixed distance bands ranging from 100 to 10,000 m depending on the species, season, and bay analyzed. Zone of indifference spatial conceptualization showed the number and location of hot spot and cold spot areas identified, as well as associated confidence intervals (90–99%) which indicated intensity of concentration.

Results

Catch Summary

Since 1986, a total of 4,464 Alligator Gar, 1,025 Spotted Gar, and 38 Longnose Gar were captured in gill nets within Galveston Bay (Table 1), and a total of 11,815 Alligator Gar, 16,381 Spotted Gar, and 54 Longnose Gar were captured in Sabine Lake (Table 2). In Galveston Bay, Alligator Gar were most abundant in East Bay, while Spotted Gar and Longnose Gar were most abundant in Trinity Bay (Table 1). In Sabine Lake, Alligator Gar were most abundant in the Salt Bayou Area, while Spotted Gar and Longnose Gar were most abundant in the Lake Area (Table 2). In general, all gar species were more abundant in the spring than the fall in both estuaries. When examining the data from the entire study period, we found that gill nets set in Galveston Bay never collected more than one Longnose Gar at a time, and only two gill nets set in Sabine Lake yielded more than one Longnose Gar in a single deployment.

Abiotic Modeling

While some abiotic variables such as temperature and turbidity act in concert with salinity to influence gar spatio-temporal dynamics, salinity showed the strongest statistical

Table 1 Summary of gar catches and associated hydrological data [mean (SD)] in Galveston Bay from 1986 to 2018

Area	Season	Alligator Gar <i>n</i>	Spotted Gar <i>n</i>	Longnose Gar <i>n</i>	Salinity (ppt)	Temperature (°C)	Dissolved oxygen (ppm)	Turbidity (NTU)
Trinity Bay	Spring	255	265	7	7.30 (7.10)	26.70 (2.90)	7.70 (1.40)	35.50 (29.50)
	Fall	107	28	2	11.60 (7.30)	24.60 (4.50)	8.20 (1.70)	19.60 (14.90)
	Total	362	293	9	9.72 (7.51)	25.50 (4.02)	7.99 (1.57)	26.40 (23.66)
Upper Galveston Bay	Spring	31	9	0	7.00 (5.28)	25.70 (3.80)	8.20 (2.10)	25.40 (21.50)
	Fall	0	0	0	12.80 (5.20)	25.60 (3.10)	7.50 (2.40)	13.80 (8.50)
	Total	31	9	0	10.07 (5.97)	25.64 (3.44)	7.85 (2.27)	19.29 (17.00)
East Bay	Spring	1277	37	4	12.40 (6.60)	26.00 (3.30)	7.50 (1.30)	32.30 (41.60)
	Fall	201	37	1	15.70 (6.80)	24.60 (4.90)	7.80 (1.60)	20.50 (23.30)
	Total	1478	74	5	14.00 (6.88)	25.34 (4.17)	7.62 (1.44)	26.54 (34.39)
Lower Galveston Bay	Spring	296	29	5	14.80 (7.80)	26.80 (3.00)	7.80 (1.60)	23.70 (23.00)
	Fall	317	9	1	18.30 (7.10)	24.50 (3.70)	8.00 (1.80)	17.50 (24.00)
	Total	613	38	6	16.62 (7.62)	25.64 (3.54)	7.90 (1.72)	20.55 (23.72)
West Bay	Spring	396	44	8	22.20 (6.50)	26.60 (2.90)	7.30 (1.30)	19.40 (16.10)
	Fall	358	7	0	24.60 (7.00)	25.60 (4.10)	7.50 (1.30)	15.40 (13.30)
	Total	754	51	8	23.38 (6.83)	26.07 (3.59)	7.40 (1.32)	17.38 (14.90)
Overall		4464	1025	38	17.21 (8.77)	25.80 (3.74)	7.66 (1.55)	21.67 (24.58)

Table 2 Summary of gar catches and associated hydrological data [mean (SD)] in Sabine Lake from 1986 to 2018

Area	Season	Alligator Gar <i>n</i>	Spotted Gar <i>n</i>	Longnose Gar <i>n</i>	Salinity (ppt)	Temperature (°C)	Dissolved oxygen (ppm)	Turbidity (NTU)
Lake Area	Spring	2837	9553	20	5.19 (5.64)	26.05 (3.33)	7.82 (1.29)	21.17 (14.36)
	Fall	1706	1612	8	10.34 (5.28)	24.84 (4.14)	7.84 (1.56)	11.11 (8.37)
	Total	4543	11,165	28	7.77 (6.04)	25.44 (3.80)	7.83 (1.43)	16.15 (12.78)
Salt Bayou Area	Spring	3734	3706	23	7.50 (6.17)	27.05 (3.64)	7.50 (1.23)	29.29 (22.82)
	Fall	3430	1442	3	11.12 (7.00)	24.99 (4.52)	7.71 (1.58)	19.63 (38.28)
	Total	7164	5148	26	9.31 (6.84)	26.02 (4.23)	7.61 (1.42)	24.50 (33.76)
Sabine Pass Area	Spring	96	68	0	9.94 (6.33)	25.02 (2.56)	7.16 (1.28)	21.92 (13.77)
	Fall	12	0	0	12.64 (5.46)	24.98 (2.89)	6.97 (1.01)	12.57 (10.37)
	Total	108	68	0	11.26 (6.01)	25.00 (2.70)	7.07 (1.11)	17.34 (12.99)
Overall		11,815	16,381	54	8.63 (6.52)	25.73 (4.03)	7.70 (1.43)	20.53 (26.25)

significance as a key driver in both estuaries of all gar species presence and abundance. Other abiotic variables did not show uniform patterns of effects on gar presence or abundance across species or estuaries (Fig. S1–S6). Visualizations and data for other abiotic variables (temperature, dissolved oxygen, and turbidity) are provided in the Supplementary Information for reference (Fig. S1–S6).

Galveston Bay Hurdle Models

In Galveston Bay, Alligator Gar are more likely to be present in areas with higher salinities ($p < 0.001$) and lower turbidity ($p = 0.032$) (Table 3; Table S7). However, Alligator Gar abundance increases in areas with lower salinities ($p < 0.001$) and higher dissolved oxygen levels ($p = 0.004$) (Table 3; Table S7). Spotted Gar are more likely to be present in higher salinities ($p < 0.0001$) and lower temperatures ($p = 0.017$), but more abundant in lower salinities ($p = 0.003$)

and higher temperatures ($p = 0.016$) (Table 3; Table S7). Longnose Gar are more likely to be present in lower salinities ($p < 0.001$) and more abundant in areas with lower dissolved oxygen levels ($p = 0.002$) (Table 3; Table S7).

Sabine Lake Hurdle Models

In Sabine Lake, Alligator Gar are more likely to be present in higher salinities ($p < 0.0001$) (Table 3; Table S7), higher temperatures ($p < 0.001$), and areas with lower turbidity ($p = 0.003$), and are more abundant in higher salinities ($p < 0.001$) and temperatures ($p < 0.001$) (Table 3; Table S7). Spotted Gar are more likely to be present in higher salinities ($p = 0.015$), and more abundant in lower salinities ($p = 0.002$), higher temperatures ($p = 0.001$), and higher turbidity ($p = 0.032$) (Table 3; Table S7). Longnose Gar are more likely to be present in higher salinities ($p < 0.0001$) (Table 3; Table S7).

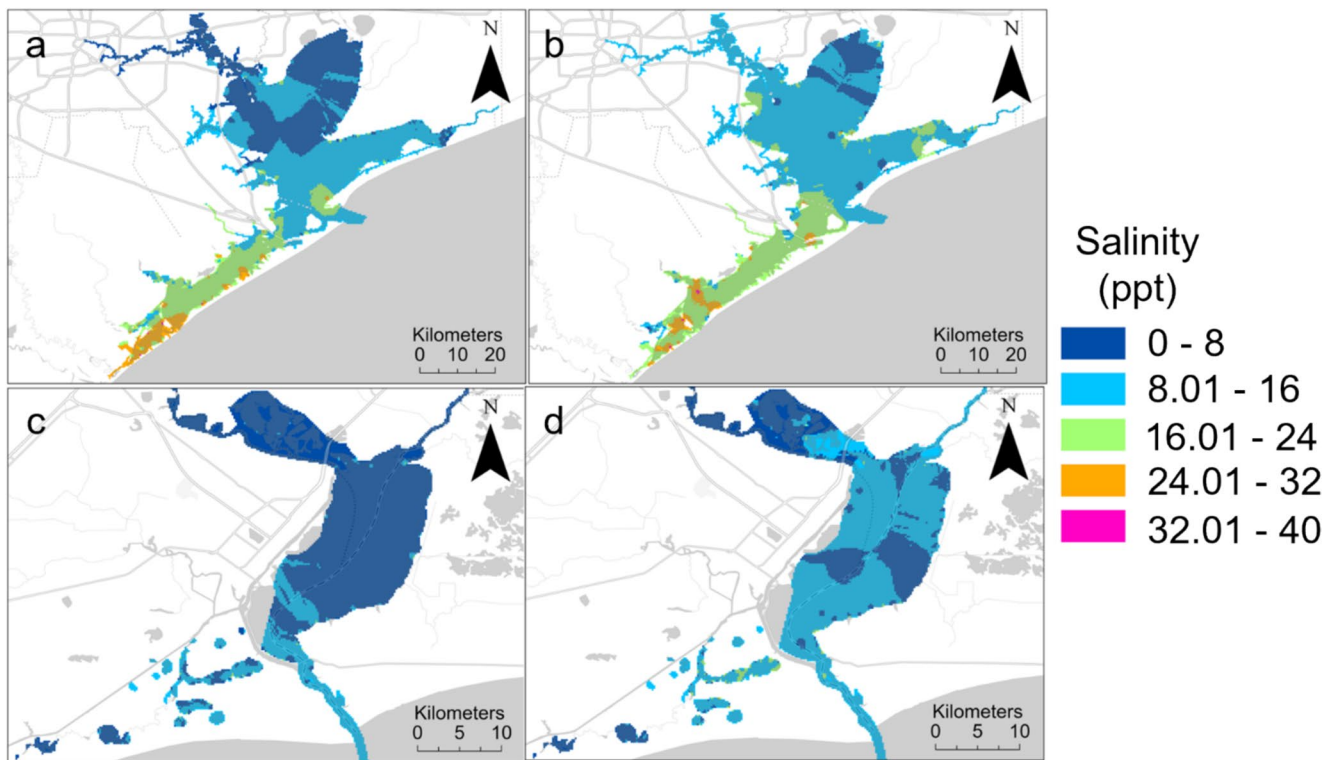


Fig. 2 Inverse distance weighted (IDW) interpolation maps of salinity values in Galveston Bay in the spring (a) and fall (b), and Sabine Lake in the spring (c) and fall (d) during the study period

cold spots with higher confidence in the Upper Galveston Bay, Lower Galveston Bay, and West Bay areas compared to fall. Spotted Gar followed a similar spatiotemporal pattern, with more spring hot spots and higher confidence on the eastern side of the estuary in the Trinity Bay, Upper Galveston Bay, and East Bay areas (Fig. 4c and d). Cold spots increased in both number, confidence, and spatial variability on the western side, in the Upper Galveston Bay, Lower Galveston Bay, and West Bay areas in the spring (Fig. 4c and d). Despite the limited sample size, Longnose Gar also exhibited similar patterns, with hot spots predominantly located on the eastern side in the Trinity Bay and East Bay areas during the spring, and no cold spots were identified (Fig. 4e and f).

Sabine Lake displayed a consistent seasonal pattern, mirroring Galveston Bay, with higher gar abundance on the eastern side of the estuary during the spring and increased numbers of hot spots in the Salt Bayou Area on the western side of the estuary in the fall (Fig. 5). For Alligator Gar, numerous hot spots were observed on the eastern side in both seasons, but spring revealed additional hot spots on the eastern side, in the Lake Area (Fig. 5a and b). In spring, both hot and cold spots increased in number and confidence (Fig. 5b). All fall Alligator Gar hot spots were in the southern half of the estuary, in the Salt Bayou and Lake areas (Fig. 5a). Spotted Gar hot spots increased in number and spread across

the Lake and Sabine Pass areas during the spring, while cold spots were more numerous and showed higher confidence intervals across the estuary (Fig. 5c and d). As in Galveston Bay, the sample size for Longnose Gar was small, but their hot spots were higher in number and showed higher confidence in the Lake Area during spring (Fig. 5f). In the fall, Longnose Gar hot spots were concentrated within the Lake Area, and no cold spots were identified (Fig. 5e).

Discussion

Salinity emerged as an important driver of distribution for all three gar species. Alligator Gar have been shown to be more tolerant of higher salinities than Spotted and Longnose Gars, explaining their greater abundance in higher salinity areas (Galveston Bay: East Bay, Lower Galveston Bay, West Bay; Sabine Lake: Salt Bayou Area, Sabine Pass Area) compared to other species within our study sites (Schwarz & Allen, 2014). Recent research has found Alligator Gar have similar gill structures to teleost fishes, allowing them to acclimate to a wide range of salinities and expand their presence and abundance in dynamic estuaries (Sorrell et al., 2026). Longnose Gar use habitats with higher salinities to a lesser degree. It has been hypothesized that their spawning habitat is correlated to lower stream flow, deeper

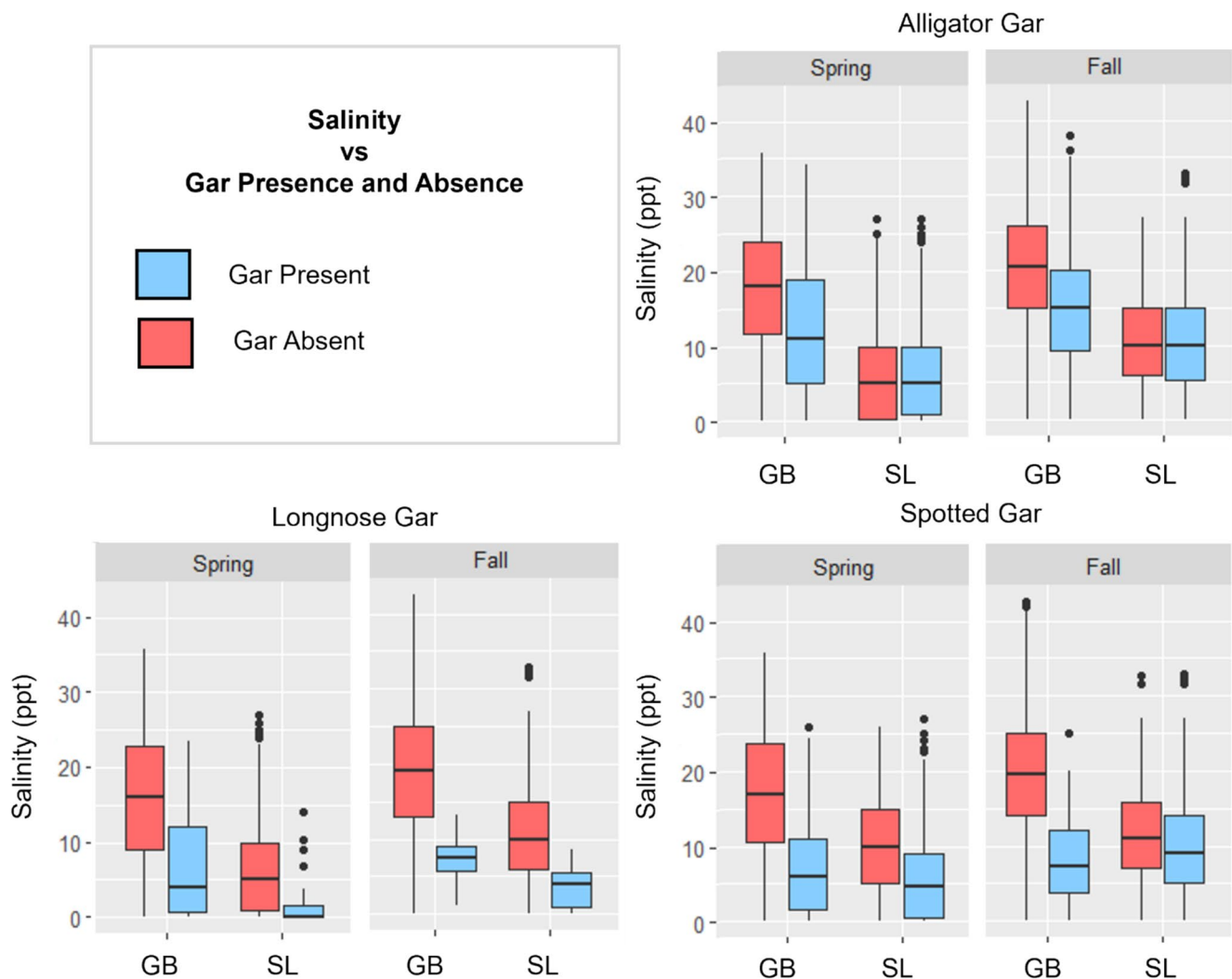


Fig. 3 Salinity values recorded in Galveston Bay (GB) and Sabine Lake (SL) each season when Alligator Gar, Spotted Gar, and Longnose Gar were present (blue) or absent (red). The boxes indicate the

interquartile range, the horizontal bar in each box indicates the median, whiskers present the minimum and maximum values recorded, and individual points indicate outliers

stream pools, and lower salinities, which may confirm why Longnose Gar were primarily found in lower salinity areas (Galveston Bay: Trinity Bay, Upper Galveston Bay; Sabine Lake: Lake Area) than other gar species (Johnson & Noltie, 1996; Smylie et al., 2016; McGrath, 2010). This salinity-associated separation of abundance between these species may also reflect a niche partitioning response to overlaps in habitat and prey resources (Svanbäck & Bolnick, 2007).

Several factors we examined (temperature, dissolved oxygen, and turbidity) did not show patterns affecting gar presence or abundance or were not statistically significant. Temperature did not consistently affect gar abundance across species and bays, possibly due to the life stage of gars assessed. Temperature reduces the development and survival of embryonic and larval gar stages in laboratory experiments, varying by species and life stage, but vulnerability of gars to temperature may be primarily confined

to early development stages which are rarely captured in gillnets and therefore were not assessed during this study (Bartnicki et al., 2021; Long et al., 2020; Martinez et al., 2021). There is also evidence that environments with very low or very high levels of dissolved oxygen negatively affect embryonic survival (Martinez et al., 2021). Dissolved oxygen levels likely do not contribute significantly to adult gar presence or abundance because adult gars are bimodal breathers, capable of consuming atmospheric oxygen in addition to respiring through their gills when dissolved oxygen levels are low (Smatresk & Cameron, 1982). Turbidity in each of the bays do not uniformly affect patterns of gar presence or abundance because turbidity levels are not geographically uniform and may be rapidly altered by seasonal major weather events, residence time of water in the estuaries, high volume and flow rates of freshwater input contributing to overbank and marsh flooding, and anthropogenic

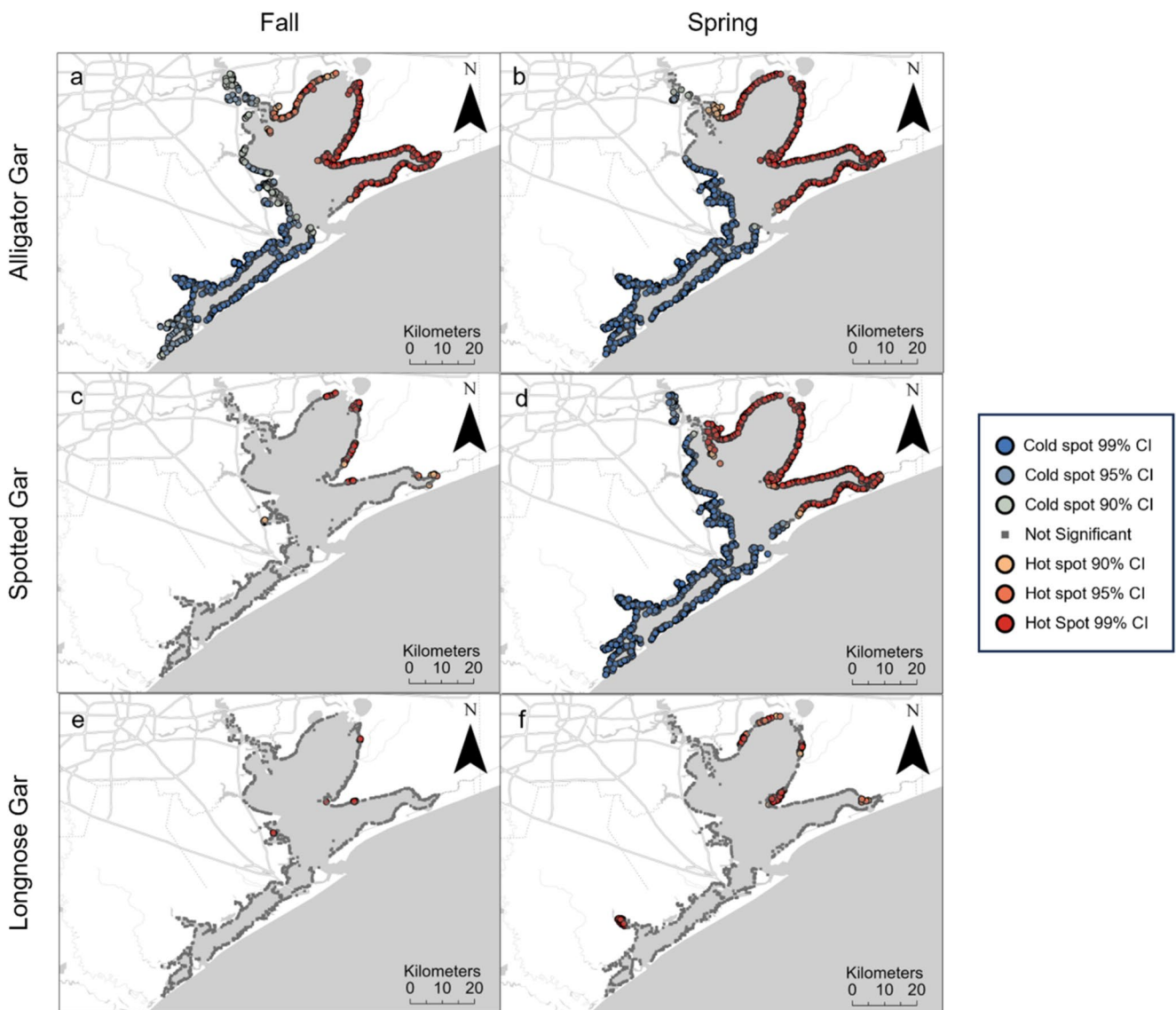


Fig. 4 Results of the hot spot analysis in Galveston Bay showing hot spots and cold spots, split by Alligator Gar in the fall (a) and spring (b), Spotted Gar in the fall (c) and spring (d), and Longnose Gar in the fall (e) and spring (f)

activity like wakes from passenger and commercial vessels disturbing seafloor and shoreline areas (Dellapenna et al., 2022; Schmidt et al., 2021). Furthermore, due to the temporal nature of TPWD's sampling scheme occurring solely in the spring and fall seasons, available data may not capture the full range of potentially statistically significant values for environmental variables. The complexity and variability of abiotic conditions in estuaries can make it difficult to identify how species respond to isolated abiotic factors, but more patterns become more evident when weighing biotic factors like reproduction.

Buckmeier et al. (2013) suggests spawning may be the most important management factor in assessing spatiotemporal dynamics of gars within estuaries. This study found that a spatiotemporal shift in gar presence occurred in both

estuaries according to season. Three gar species shifted from the western half of the estuarine system to the eastern half from the fall to spring. While many factors could be responsible for these patterns, a potential driver of these seasonal shifts is gar spawning behavior. The observed spatiotemporal shift coincides with spawning periods for all three species of gar, underscoring the potential importance of estuarine environments as essential fish habitat for spawning activities in gar populations. Previous literature suggests that gars prefer floodplain areas that are clear, less disturbed, and shallow for spawning (Brinkman, 2008; Ferrara, 2001; Gray et al., 2012; Snedden et al., 1999). Vegetation presence is also a documented important factor for gar spawning, functioning as a surface for gars to lay their eggs on (Adams et al., 2024; Frenette & Snow, 2016; Hawthorne

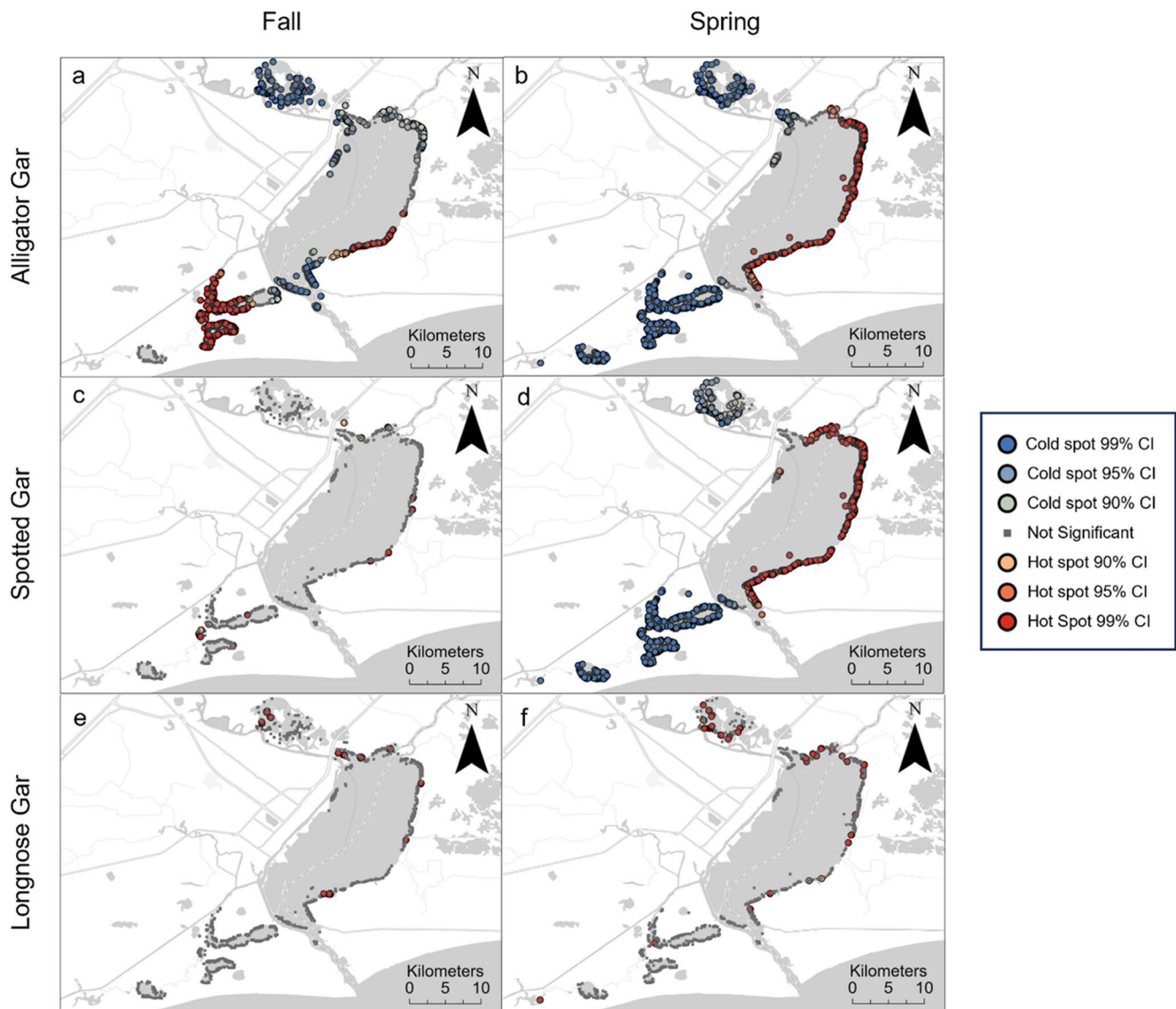


Fig. 5 Results of the hot spot analysis in Sabine Lake showing hot spots and cold spots, split by Alligator Gar in the fall (a) and spring (b), Spotted Gar in the fall (c) and spring (d), and Longnose Gar in the fall (e) and spring (f)

et al., 2024). Vegetated areas are also important habitat for larval gars because they serve as submerged substrate for larvae to adhere to with their attachment organs during post-hatch development, there is an abundance of small prey available, and vegetation offers shelter from predation (Adams et al., 2024; McAllister et al., 2022; Pinion et al., 2021; Sepúlveda-Quiroz et al., 2023). There is decreased vegetation density and increased turbidity near marsh edges on the western side of both estuaries due to major shipping channels (Houston Ship Channel in Galveston Bay and Sabine-Neches Waterway in Sabine Lake) and oil refineries (Irvine et al., 1997; Nylund et al., 2021). These anthropogenic developments which restrict habitat connectivity may reduce the suitability of the western side of each estuary for

gar spawning events (Silinski et al., 2015). Another explanation for the seasonal differences in presence and abundance may be decreased fish movement during winter. Gars are known to reduce daily rates and range of movement during the winter, likely for energy conservation (Fontaine et al., 2026; Kluender et al., 2017; Snedden et al., 1999). Seasonal prey availability is also likely a contributing factor, contracting in the winter as environmental conditions become less favorable and necessitate movement of gars to more optimal foraging grounds (Fontaine et al., 2026; Livernois et al., 2021).

The results of this study indicate that gar species that overlap spatially in estuarine habitat tend to separate seasonally into environmental niches driven by salinity and

preferred spawning habitat. Galveston Bay's higher salinity levels, attributed to more saltwater ingress locations, create less suitable gar habitat than Sabine Lake. Sabine Lake's lower and more homogeneous salinity levels, likely caused by Sabine Pass acting as a bottleneck for saltwater and freshwater exchange, uniquely positions the estuary as a better environment for estuarine gar populations. This would account for increased abundance of all gar species in Sabine Lake compared to Galveston Bay, despite a large difference in size, geological composition, and hydrological processes. (Daugherty et al., 2017). In addition, the Sabine Lake system also has more undeveloped marsh habitat surrounding it than the Galveston Bay system. Over 240,000 acres of protected habitat is provided by the Sabine National Wildlife Refuge, McFaddin National Wildlife Refuge, and Texas Point National Wildlife Refuge. The Galveston Bay system hosts the Jocelyn Nungaray National Wildlife Refuge and Moody National Wildlife Refuge in the East Bay, and Brazoria National Wildlife Refuge, encompassing less than 100,000 acres. In both bay systems, gars are more abundant in areas near a national wildlife refuge compared to areas near developed land. This highlights the importance of preserving valuable habitat for fish species who rely on undeveloped protected habitat and emphasizes the value that national wildlife refuges add to local ecosystems.

Results presented here will be important to consider as recreational fisheries for these species in northern Gulf of Mexico estuaries continue to grow and these estuaries are increasingly subjected to increased anthropogenic development of shipping lanes and refineries (Buckmeier et al., 2016; Charles, 2005; Snow et al., 2018). Regionally, this study highlights how fisheries managers may consider the unique challenges that Sabine Lake fish populations face due to the Texas-Louisiana state line dividing the estuary system into two management regions. Cooperative efforts on management policies between the states of Texas and Louisiana will be crucial for maintaining healthy gar populations. The results of this study strongly support recent suggestions for localized management of gar populations as opposed to broader state management (Buckmeier et al., 2013; Daugherty et al., 2017; Ellard et al., 2023; Schlechte et al., 2020). Future research should investigate specific salinity thresholds of gar species across ontogenetic stages to better predict how anthropogenic and environmental changes may impact species assemblages in estuaries (Bacheler et al., 2009; Matich et al., 2017). Confirmation of the eastern sides of Galveston Bay and Sabine Lake as spawning grounds for gars would also benefit conservation management and help delineate essential fish habitat.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s12237-026-01826-y>.

Acknowledgments This work was made possible in part by the Aggies Commit to Excellence Scholar program at Texas A&M University at Galveston and the Texas A&M Undergraduate Research Scholars program. The authors thank the students of the Shark Biology and Fisheries Science Lab and the Fisheries Ecology Lab at Texas A&M University at Galveston for their valuable feedback and discussion. The authors also thank the Texas Parks and Wildlife Coastal Fisheries Division teams in Galveston Bay and Sabine Lake for their work on the gill net sampling surveys. Data was provided by the Texas Parks and Wildlife Department's Coastal Fisheries Division, courtesy of Mark Fisher.

Author Contributions Anna N. DeMotte, Emily N. Meese, and R.J. David Wells conceptualized the study. Anna N. DeMotte and Emily N. Meese acquired funding for the study. Data preparation and formal analyses were conducted by Anna N. DeMotte and Emily N. Meese. Anna N. DeMotte prepared the original draft of the manuscript and led all revisions. Manuscript reviews and edits were provided by Emily N. Meese, R.J. David Wells, Carey G. Gelpi, and Christine C. Jensen. Emily N. Meese and R.J. David Wells supervised the study. All authors reviewed and approved the final manuscript for submission.

Funding This work was supported in part by an Institutional Grant NA18OAR4170088, to the Texas Sea Grant College Program from the National Sea Grant Office, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of Texas Sea Grant.

Data Availability The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors have no relevant financial or non-financial interests to declare.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Able, K. W. (2005). A re-examination of fish estuarine dependence: evidence for connectivity between estuarine and ocean habitats. *Estuarine coastal and shelf science*, 64, 5–17. <https://doi.org/10.1016/j.ecss.2005.02.002>
- Adams, S. R., Inebnit, T. E., Lewis, L. C., Naus, C. J., Kluender, E., & Spooner, G. G. (2024). Spawning Ecology and Spawning Site

- Fidelity of Alligator Gar, *Atractosteus spatula*, in the Fourche LaFave River: Implications for River-Floodplain Management and Alligator Gar Conservation. *Southeastern Fishes Council Proceedings*, 1, 3. <https://doi.org/10.7290/sfcp64n8y2>
- Amundsen, P., Bøhn, T., Popova, O., Staldivik, F., Reshetnikov, Y., Kashulin, N., & Lukin, A. (2003). Ontogenetic niche shifts and resource partitioning in a subarctic piscivore fish guild. *Hydrobiologia*, 497, 109–119. <https://doi.org/10.1023/A:1025465705717>
- Bacheler, N. M., Paramore, L. M., Buckel, J. A., & Hightower, J. E. (2009). Abiotic and biotic factors influence the habitat use of an estuarine fish. *Marine Ecology Progress Series*, 377, 263–277. <https://doi.org/10.3354/meps07805>
- Barletta, M., Barletta-Bergan, A., Saint-Paul, U., & Hubold, G. (2005). The role of salinity in structuring the fish assemblages in a tropical estuary. *Journal of Fish Biology*, 66, 45–72. <https://doi.org/10.1111/j.0022-1112.2005.00582.x>
- Bartnicki, J., Snow, R. A., Taylor, A. T., & Butler, C. J. (2021). Critical thermal minima of alligator gar (*Atractosteus spatula*, [Lacépède, 1803]) during early life stages. *Journal of Applied Ichthyology*, 37, 572–577. <https://doi.org/10.1111/jai.14209>
- Betty, E. L., Bollard, B., Murphy, S., Ogle, M., Hendriks, H., Orams, M. B., & Stockin, K. A. (2020). Using emerging hot spot analysis of stranding records to inform conservation management of a data-poor cetacean species. *Biodiversity and Conservation*, 29, 643–665. <https://doi.org/10.1007/s10531-019-01903-8>
- Bi, R., Jiao, Y., Weaver, L. A., Greenlee, B., McClair, G., Kipp, J., Wilke, K., Haas, C., & Smith, E. (2021). Environmental and anthropogenic influences on spatiotemporal dynamics of *Alosa* in Chesapeake Bay tributaries. *Ecosphere*, 12, e03544. <https://doi.org/10.1002/ecs2.3544>
- Bohn, S. E., Kreiser, B. R., Williford, D., Anderson, J., & Karel, W. (2023). To all the gar I loved before: range-wide population genetic structure in Alligator Gar. *Conservation Genetics*, 24, 501–521. <https://doi.org/10.1007/s10592-023-01516-3>
- Bouyer, Y., Rigot, T., Panzacchi, M., Van Moorter, B., Poncin, P., Beudels-Jamar, R., Odden, J., & Linnell, J. D. (2015). Using zero-inflated models to predict the relative distribution and abundance of roe deer over very large spatial scales. *Annales Zoologici Fennici*, 52, 66–76. <https://doi.org/10.5735/086.052.0206>
- Brinkman, E. L. (2008). *Contributions to the life history of Alligator Gar, Atractosteus spatula (Lacépède), in Oklahoma*. Master's Thesis (p. 37pp). Oklahoma State University.
- Brooks, M. E., Kristensen, K., van Benthem, K. J., Magnusson, A., Berg, C. W., Nielsen, A., Skaug, H. J., Maechler, M., & Bolker, B. M. (2017). glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling. *The R Journal*, 9(2), 378–400. <https://doi.org/10.32614/RJ-2017-066>
- Buckmeier, D. L., Smith, N. G., & Daugherty, D. J. (2013). Alligator Gar Movement and Macrohabitat Use in the Lower Trinity River, Texas. *Transactions of the American Fisheries Society*, 142, 1025–1035.
- Buckmeier, D. L., Smith, N. G., Schlechte, J. W., Ferrara, A. M., & Kirkland, K. (2016). Characteristics and conservation of a trophy Alligator Gar population in the middle Trinity River, Texas. *Journal of the Southeastern Association of Fish and Wildlife Agencies*, 3, 33–38.
- Cameron, A. C., & Trivedi, P. K. (2003). Essentials of count data regression. In *A companion to theoretical econometrics*, B.H. Baltagi (Ed.) 331. <https://doi.org/10.1002/9780470996249.ch16>
- Catchpole, S., Rivera, R., Hernández, C., De La Pena, J., & González, P. (2019). Predicting spatial distribution patterns and hotspots of fish assemblage in a coastal basin of the central-south of Chile, by geostatistical techniques. *Journal of Limnology*, 78, 220–232. <https://doi.org/10.4081/jlimnol.2019.1881>
- Charles, J. S. (2005, February). Economic activity associated with recreational fishing along the Texas Gulf Coast. Texas State University Digital Library. Retrieved February 26, 2025, from <https://digital.library.txst.edu/server/api/core/bitstreams/16359b6d-dce1-440d-b743-f53b36e9d00f/content>
- Daugherty, D. J., Pangle, K. L., Karel, W., Baker, F., Robertson, C. R., Buckmeier, D. L., Smith, N. G., & Boyd, N. (2017). Population structure of Alligator Gar in a Gulf Coast river: insights from otolith microchemistry and genetic analyses. *North American Journal of Fisheries Management*, 37, 337–348. <https://doi.org/10.1080/02755947.2016.1269029>
- Daugherty, D. J., Schlechte, J. W., & McDonald, D. L. (2018). Alligator Gars in Texas coastal bays: long-term trends and environmental influences. *Transactions of the American Fisheries Society*, 147, 653–664. <https://doi.org/10.1002/tafs.10041>
- Dellapenna, T. M., Hoelscher, C., Hill, L., Critides, L., Salgado, V., Bell, M., Mukaimi, A., Du, M. E., Park, J., K., & Knap, A. H. (2022). Hurricane Harvey delivered a massive load of mercury-rich sediment to Galveston Bay, TX, USA. *Estuaries and Coasts*, 45, 428–444. <https://doi.org/10.1007/s12237-021-00990-7>
- Ellard, J. K., Roberts, H. C., Daugherty, D. J., Fleming, B. P., Acre, M. R., & Perkin, J. S. (2023). Scale-dependent tradeoffs between habitat and time in explaining Alligator Gar (*Atractosteus spatula*) movement. *Environmental Biology of Fishes*. <https://doi.org/10.1007/s10641-023-01473-3>
- Fernandes, I. M., Henriques-Silva, R., Penha, J., Zuanon, J., & Peres-Neto, P. R. (2014). Spatiotemporal dynamics in a seasonal meta-community structure is predictable: the case of floodplain-fish communities. *Ecography*, 37, 464–475. <https://doi.org/10.1111/j.1600-0587.2013.00527.x>
- Ferrara, A. M. (2001). *Life-history strategy of Lepisosteidae: implications for the conservation and management of Alligator Gar*. Doctoral Dissertation (p. 126pp). Auburn University.
- Fontaine, P., Jensen, C. C., Matich, P., Rooker, J. R., & Wells, R. D. (2024). Predicting habitat suitability for the co-occurrence of an estuarine mesopredator and two top predatory fishes. *Frontiers in Fish Science*, 2, 1443923. <https://doi.org/10.3389/frish.2024.1443923>
- Fontaine, P., Jensen, C. C., Matich, P., Rooker, J. R., & Wells, D., R. J. (2026). Spatial dynamics of three estuarine predatory fishes in a subtropical estuary. *Marine Biology*, 173(1), 178. <https://doi.org/10.1007/s00227-026-04930-6>
- Frenette, B. D., & Snow, R. (2016). Natural habitat conditions in a captive environment lead to spawning of Spotted Gar. *Transactions of the American Fisheries Society*, 145(4), 835–838. <https://doi.org/10.1080/00028487.2016.1167776>
- Gonzalez, L. A., Quigg, A., Steichen, J. L., Gelwick, F. P., & Lester, L. J. (2021). A new approach to functionally assess estuarine fish communities in response to hydrologic change. *Estuaries and Coasts*, 44, 1118–1131. <https://doi.org/10.1007/s12237-020-00824-y>
- Gray, S. M., Chapman, L. J., & Mandrak, N. E. (2012). Turbidity reduces hatching success in threatened Spotted Gar (*Lepisosteus oculatus*). *Environmental Biology of Fishes*, 94, 689–694. <https://doi.org/10.1007/s10641-012-9999-z>
- Hawthorne, W. H., Sulak, K. J., & Walsh, S. J. (2024). Spawning within floating vegetation: novel underwater observations of egg deposition in Longnose Gar (*Lepisosteus osseus*). *Southeastern Naturalist*, 23(4), 414–424. <https://doi.org/10.1656/058.023.0401>
- Hu, K., Meselhe, E. A., & Reed, D. J. (2023). Understanding drivers of salinity and temperature dynamics in Barataria Estuary, Louisiana. *Journal of Geophysical Research: Oceans*, 128, e2023JC019635. <https://doi.org/10.1029/2023JC019635>
- Irvine, K. N., Droppo, I. G., Murphy, T. P., & Lawson, A. (1997). Sediment resuspension and dissolved oxygen levels associated with ship traffic: Implications for habitat remediation. *Water Quality*

- Research Journal, 32, 421–438. <https://doi.org/10.2166/wqrj.19.97.027>
- Johnson, B. L., & Noltie, D. B. (1996). Migratory dynamics of stream-spawning Longnose Gar (*Lepisosteus osseus*). *Ecology of Freshwater Fish*, 5, 97–107. <https://doi.org/10.1111/j.1600-0633.1996.tb00041.x>
- Kleisner, K. M., Fogarty, M. J., McGee, S., Barnett, A., Fratanoni, P., Greene, J., Hare, J. A., Lucey, S. M., McGuire, C., & Odell, J. (2016). The effects of sub-regional climate velocity on the distribution and spatial extent of marine species assemblages. *PLoS one*, 11, e0149220. <https://doi.org/10.1371/journal.pone.0149220>
- Kluender, E. R., Adams, R., & Lewis, L. (2017). Seasonal habitat use of Alligator Gar in a river-floodplain ecosystem at multiple spatial scales. *Ecology of Freshwater Fish*, 26(2), 233–246. <https://doi.org/10.1111/eff.12270>
- Lackmann, A. R., Watkinson, D. A., David, S. R., Scarnecchia, D. L., & Docker, M. F. (2024). From neglect toward enlightenment: the conservation of native fishes in the twenty-first century. *Environmental Biology of Fishes*, 107, 1305–1326. <https://doi.org/10.1007/s10641-024-01655-7>
- Lewin, W., Freyhof, J., Huckstorf, V., Mehner, T., & Wolter, C. (2010). When no catches matter: Coping with zeros in environmental assessments. *Ecological Indicators*, 10, 572–583. <https://doi.org/10.1016/j.ecolind.2009.09.006>
- Livernois, M. C., Fujiwara, M., Fisher, M., & Wells, R. D. (2021). Seasonal patterns of habitat suitability and spatiotemporal overlap within an assemblage of estuarine predators and prey. *Marine Ecology Progress Series*, 668, 39–55. <https://doi.org/10.3354/meps13700>
- Livernois, M. C., Rezek, R. J., & Wells, R. D. (2024). Spatial and ontogenetic trophic dynamics of co-occurring predatory fishes in a Northern Gulf of Mexico estuary. *Estuaries and Coasts*, 47, 1119–1138. <https://doi.org/10.1007/s12237-024-01361-8>
- Long, J. M., Snow, R. A., & Porta, M. J. (2020). Effects of temperature on hatching rate and early development of alligator gar and spotted gar in a laboratory setting. *North American Journal of Fisheries Management*, 40, 661–668. <https://doi.org/10.1002/nafm.10397>
- Love, J. W. (2004). Age, growth, and reproduction of Spotted Gar, *Lepisosteus oculatus* (Lepisosteidae), from the Lake Pontchartrain Estuary, Louisiana. *The Southwestern Naturalist*, 18–23. [https://doi.org/10.1894/0038-4909\(2004\)049%3C0018:AGAROS%3E2.0.CO;2](https://doi.org/10.1894/0038-4909(2004)049%3C0018:AGAROS%3E2.0.CO;2)
- Marsaly, B., Daugherty, D., Shipley, O. N., Gelpi, C., Boyd, N., Davis, J., Fisher, M., & Matich, P. (2023). Contrasting ecological roles and flexible trophic interactions of two estuarine apex predators in the western Gulf of Mexico. *Marine Ecology Progress Series*, 709, 55–76. <https://doi.org/10.3354/meps14281>
- Martínez, G., Peña, E., Martínez, R., Camarillo, S., Burggren, W., & Álvarez, A. (2021). Survival, growth, and development in the early stages of the tropical gar *Atractosteus tropicus*: developmental critical windows and the influence of temperature, salinity, and oxygen availability. *Fishes*, 6, 5. <https://doi.org/10.3390/fishes6010005>
- Martínez-Andrade, F. (2018). *Marine resource monitoring operations manual*. Texas Parks and Wildlife Department, Coastal Fisheries Division.
- Matich, P., Mohan, J. A., Plumlee, J. D., Tinhan, T., Wells, R. J. D., & Fisher, M. (2017). Factors shaping the co-occurrence of two juvenile shark species along the Texas Gulf Coast. *Marine Biology*, 164, 1–16. <https://doi.org/10.1007/s00227-017-3173-2>
- McAllister, K., Drake, D. A. R., & Power, M. (2022). Habitat preferences of young-of-year Spotted Gar (*Lepisosteus oculatus*) in Rondeau Bay, Lake Erie. *Canadian Journal of Zoology*, 101, 1–10. <https://doi.org/10.1139/cjz-2022-0081>
- McGrath, P. E. (2010). *The life history of Longnose Gar, Lepisosteus osseus, an apex predator in the tidal waters of Virginia*. Doctoral Dissertation (p. 177pp). The College of William and Mary.
- Mosman, J. D., Gilby, B. L., Olds, A. D., Gaines, G., Borland, L. A., H. P., & Henderson, C. J. (2023). Multiple fish species supplement predation in estuaries despite the dominance of a single consumer. *Estuaries and Coasts*, 46, 891–905. <https://doi.org/10.1007/s12237-023-01184-z>
- Nylund, A. T., Arneborg, L., Tengberg, A., Mallast, U., & Hassellöv, I. (2021). In situ observations of turbulent ship wakes and their spatiotemporal extent. *Ocean Science*, 17, 1285–1302. <https://doi.org/10.5194/os-17-1285-2021>
- O’Connell, M. T., Shepherd, T. D., O’Connell, A. M., & Myers, R. A. (2007). Long-term declines in two apex predators, bull sharks (*Carcharhinus leucas*) and Alligator Gar (*Atractosteus spatula*), in lake pontchartrain, an oligohaline estuary in southeastern Louisiana. *Estuaries and Coasts*, 30, 567–574. <https://doi.org/10.1007/BF02841954>
- Ogbodo, C. O., Fitzgerald, R. M., Fuller, C., Lee, J., Perea, R., & Polanco-Gonzalez, J. (2024). Intercomparison of Surface Currents Obtained Using SCHISM and the HF Radar Data in Galveston Bay and Sabine Lake, Texas. *Journal of Marine Science and Engineering*, 12, 1962. <https://doi.org/10.3390/jmse12111962>
- Pinion, A. K., Siegel, D. S., Britz, R., Martínez-García, R., Álvarez-González, C. A., & Conway, K. W. (2021). The larval attachment organ of the tropical gar *Atractosteus tropicus* Gill, 1863 (Lepisosteiformes: Lepisosteidae). *Journal of Fish Biology*, 99, 418–424. <https://doi.org/10.1111/jfb.14733>
- Schlechte, J. W., Daugherty, D. J., Smith, N. G., & Buckmeier, D. L. (2020). Angler Practices and Preferences for Managing Alligator Gar in Texas. *Journal of the Southeastern Association of Fish and Wildlife Agencies*, 8, 23–31.
- Schmidt, N., Dellapenna, T., & Lin, P. (2021). ⁷Be/²¹⁰Pb xs Ratio-Derived Age and Residence Time of Suspended Sediments in Galveston Bay. *Frontiers in Marine Science*, 8, 703945. <https://doi.org/10.3389/fmars.2021.703945>
- Schwartz, F. J. (2003). Longnose Gar, *Lepisosteus osseus* (Family Lepisosteidae) in North Carolina, especially the Cape Fear River. *Journal of the North Carolina Academy of Science*, 119, 26–32.
- Schwarz, D. E., & Allen, P. J. (2014). Effects of salinity on growth and ion regulation of juvenile Alligator Gar *Atractosteus spatula*. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, 169, 44–50. <https://doi.org/10.1016/j.cbpa.2013.12.012>
- Sepúlveda-Quiroz, C. A., Álvarez-Villagomez, C. S., Mendoza-Porras, O., Peña-Marín, E. S., Maytorena-Verdugo, C. I., Pérez-Jiménez, G. M., Jesus-Contreras, R., Álvarez-González, C. A., & Martínez-García, R. (2023). Attack behavior leading cannibalism in tropical gar (*Atractosteus tropicus*) larvae under different tank colors and shelter type. *Aquaculture*, 563, 738991. <https://doi.org/10.1016/j.aquaculture.2022.738991>
- Sheaves, M., Sheaves, J., Stegemann, K., & Molony, B. (2013). Resource partitioning and habitat-specific dietary plasticity of two estuarine sparid fishes increase food-web complexity. *Marine and Freshwater Research*, 65, 114–123. <https://doi.org/10.1071/MF12348>
- Silinski, A., Heuner, M., Schoelynck, J., Puijalon, S., Schröder, U., Fuchs, E., Troch, P., Bouma, T. J., Meire, P., & Temmerman, S. (2015). Effects of Wind Waves versus Ship Waves on Tidal Marsh Plants: A Flume Study on Different Life Stages of *Scirpus maritimus*. *PLoS one*, 10, e0118687. <https://doi.org/10.1371/journal.pone.0118687>
- Smatresk, N. J., & Cameron, J. N. (1982). Respiration and acid-base physiology of the spotted gar, a bimodal breather: III. Response to a transfer from fresh water to 50% sea water, and control of

- ventilation. *Journal of Experimental Biology*, 96, 295–306. <https://doi.org/10.1242/jeb.96.1.295>
- Smith, N. G., Daugherty, D. J., Schlechte, J. W., & Buckmeier, D. L. (2018). Modeling the Responses of Alligator Gar Populations to Harvest under Various Length-Based Regulations: Implications for Conservation and Management. *Transactions of the American Fisheries Society*, 147, 665–673. <https://doi.org/10.1002/tafs.10040>
- Smith, N. G., Daugherty, D. J., Binkman, E. L., Wegener, M. G., Kreiser, B. R., Ferrara, A. M., Kimmel, K. D., & David, S. R. (2020). Advances in Conservation and Management of the Alligator Gar: A Synthesis of Current Knowledge and Introduction to a Special Section. *North American Journal of Fisheries Management*, 40, 527–543. <https://doi.org/10.1002/nafm.10369>
- Smylie, M., Shervette, V., & McDonough, C. (2016). Age, Growth, and Reproduction in Two Coastal Populations of Longnose Gars. *Transactions of the American Fisheries Society*, 145, 120–135. <https://doi.org/10.1080/00028487.2015.1111256>
- Snedden, G. A., Kelso, W. E., & Rutherford, D. A. (1999). Diel and seasonal patterns of Spotted Gar movement and habitat use in the lower Atchafalaya River Basin, Louisiana. *Transactions of the American Fisheries Society*, 128, 144–154. [https://doi.org/10.1577/1548-8659\(1999\)128%3C0144:DASPOS%3E2.0.CO;2](https://doi.org/10.1577/1548-8659(1999)128%3C0144:DASPOS%3E2.0.CO;2)
- Snow, R. A., Porta, M. J., Simmons, R. W., & Bartnicki, J. B. (2018). Early Life History Characteristics and Contribution of Stocked Juvenile Alligator Gar in Lake Texoma, Oklahoma. *Proceedings of the Oklahoma Academy of Science*, 98, 46–54.
- Sorrell, B. P., Rivers, O. S., Wilson, J. M., & Allen, P. J. (2026). Effects of Salinity on Gill Ultrastructure of Alligator Gar *Atractosteus spatula*. *Journal of Experimental Zoology Part A: Ecological and Integrative Physiology*, 345, 427–439. <https://doi.org/10.1002/jez.70076>
- St. George, J. R., Petersen, S. D., Roth, J. D., Ferguson, S. H., & Yurkowski, D. J. (2023). Habitat coupling dynamics of mobile consumers along a freshwater and marine resource gradient in a sub-Arctic estuarine system. *Estuarine Coastal and Shelf Science*, 292, 108449. <https://doi.org/10.1016/j.ecss.2023.108449>
- Steel, E. A., Kennedy, M. C., Cunningham, P. G., & Stanovick, J. S. (2013). Applied statistics in ecology: common pitfalls and simple solutions. *Ecosphere*, 4, 1–13. <https://doi.org/10.1890/ES13-00160.1>
- Steichen, J. L., & Quigg, A. (2018). Fish species as indicators of freshwater inflow within a subtropical estuary in the Gulf of Mexico. *Ecological Indicators*, 85, 180–189. <https://doi.org/10.1016/j.ecoind.2017.10.018>
- Stevens, P. W., Paperno, R., Beal, J. L., MacDonald, T. C., Miller, H. N., Klarmann, P. A., & Malinowski, C. R. (2022). Identification of fish habitat hotspots for use in prioritizing conservation and restoration projects in coastal rivers. *Environmental Biology of Fishes*, 106, 221–235. <https://doi.org/10.1007/s10641-022-01226-8>
- Stukey, J., Narasimhan, B., Srinivasan, R., Bay, G., & Bay, M. A. (2004). San Antonio Bay, and Sabine Lake lower-watershed multi-year land-use and land cover classifications and curve numbers TWDB Contract# 0804830788. Spatial Sciences Lab, Department of Ecosystem Science and Management, and Texas A&M University: College Station, TX, USA.
- Svanbäck, R., & Bolnick, D. I. (2007). Intraspecific competition drives increased resource use diversity within a natural population. *Proceedings of the Royal Society B: Biological Sciences*, 274, 839–844. <https://doi.org/10.1098/rspb.2006.0198>
- Watson, R. L. (1999, September). *Severe Beach Erosion Caused by Permanent Beach Sand Loss Through Rollover Fish Pass, Bolivar Peninsula, Texas*. Texas Coast Geology. Retrieved February 26, 2025, from <http://texascoastgeology.com/papers/rollover.pdf>
- Whitfield, A. K. (2021). Estuaries—how challenging are these constantly changing aquatic environments for associated fish species? *Environmental Biology of Fishes*, 104, 517–528. <https://doi.org/10.1007/s10641-021-01085-9>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.