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Influence of nearby environment on recreational bycatch of sea turtles at fishing piers in the eastern Gulf of Mexico

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ABSTRACT: Incidental bycatch of sea turtles from recreational fisheries is generally undocumented globally. At Gulf of Mexico fishing piers in the USA, bycatch is a source of injury and potential mortality of sea turtles. Recreational sea turtle bycatch has grown substantially over the last 6 yr, especially at the Navarre Beach Fishing Pier (NW Florida); the reasons for the increase and the impacts this has on the recovery of northern Gulf of Mexico sea turtle populations are largely unknown. In particular, the reasons why fishing piers are attracting sea turtles are not well understood or if the environmental context of other nearby habitats contributes to the bycatch. Using GIS, we analyzed potential environmental predictors of total sea turtle bycatch, across green sea turtles *Chelonia mydas*, loggerhead sea turtles *Caretta caretta*, and Kemp's ridley sea turtles *Lepidochelys kempii*. We collated bycatch and environmental data from 20 Florida Gulf of Mexico fishing piers. We statistically assessed relationships using generalized additive models and selected the best fit model using the information-theoretic approach. We found that tonnage of nearby artificial reefs (based on defined home range and core use areas) and distance to nearest seagrass bed exhibit positive relationships with green sea turtle bycatch. For combined loggerhead and Kemp's ridley bycatch, area of preserved water, distance to nearest seagrass bed, tonnage of nearby artificial reefs, and latitude of fishing piers were all predictors in the confidence set, but the shape of the relationships is variable and nonlinear. Further examination of sea turtle bycatch, occupancy of piers, and environmental factors pertaining to sea turtles will likely improve mitigation measures for recreational bycatch.

KEY WORDS: Artificial habitats · Seagrass · Conservation · GIS · Incidental catch/capture · Recreational fishing · Fisheries management

1. INTRODUCTION

Incidental capture of marine organisms, also known as bycatch, and its effects on these organisms are relatively well documented for commercial fisheries (Crowder et al. 1995, Read et al. 2006, Davies et al. 2009, Carruthers & Neis 2011). Efforts to reduce commercial bycatch have led to the design of technologies and procedures aimed at minimizing the potential for bycatch of protected species (Read et al. 2006, Coleman et al. 2016). While commercial bycatch represents a large portion of overall bycatch, recreational bycatch poses similar risks to marine species, especially endangered species; however, the patterns, dynamics, and even total amounts of recreational bycatch are not as well understood or documented (Davies et al. 2009). While most recreational hook-and-line bycatch is broadly distributed, sea tur-

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tle bycatch at fishing piers is localized and seasonal (Lamont et al. 2021, Sea Turtle Stranding and Salvage Network [STSSN] unpubl. data). Higher bycatch rates are observed during the summer months, especially when certain fish stocks are in season, e.g. Florida pompano *Trachinotus carolinus* season in northwestern Florida (FL), and lower in the winter when fishing intensity is decreased (Schrandt 2015, Lewin et al. 2019, Lamont et al. 2021). Reducing bycatch requires fisheries stakeholder engagement, an effective regulatory authority, and the ability to mitigate bycatch. Therefore, bycatch reduction remains an expensive and laborious conservation activity.

Fishing piers are an important source of recreational bycatch and entanglement for avian, fish, and other megafaunal species, such as sea turtles (Donnelly-Greenan et al. 2019, Cook et al. 2020, Pate et al. 2021). In fact, recreational bycatch of sea turtles has been documented at fishing piers along the US Gulf of Mexico (GoMx) by STSSN for >40 yr (Canon et al. 1994, STSSN unpubl. data, https://www.fisheries.noaa.gov/national/marine-life-distress/sea-turtle-stranding-and-salvage-network). Most of the existing research focuses on bycatch of Kemp's ridley sea turtles *Lepidochelys kempii* at fishing piers in Texas and Mississippi following anomalously high levels of bycatch in 1992, 2002, and from 2012 to 2015 (Canon et al. 1994, Rudloe & Rudloe 2005, Seney 2008, 2016, Coleman et al. 2016, Cook et al. 2020, Howell et al. 2021).

Similarly, northeastern GoMx fishing piers also experience recreational sea turtle bycatch; however, green sea turtles *Chelonia mydas* and loggerhead sea turtles *Caretta caretta* are more commonly incidentally captured (Lamont et al. 2021, STSSN unpubl. data). Three species of sea turtles (loggerhead, Kemp's ridley, green) that frequent the GoMx are incidentally captured at FL fishing piers (Gulfarium C.A.R.E. Center unpubl. data, STSSN unpubl. data). All these species are Vulnerable (loggerhead), Endangered (green), or Critically Endangered (Kemp's ridley) on a global scale, according to the IUCN. Further, within the US, sea turtles in the north Atlantic are listed as threatened (loggerhead and green) or endangered (Kemp's ridley) under the Endangered Species Act.

Recreational sea turtle bycatch at Navarre Beach Fishing Pier (NP) is the highest reported along the FL GoMx coast, and predominantly consists of green sea turtles (Lamont et al. 2021, Gulfarium C.A.R.E. Center unpubl. data, STSSN unpubl. data; our Fig. 1). While the total number of reported incidentally caught sea turtles is lower than the incidence rates previously reported in Mississippi from 2012 to 2015 (n = 1012, Cook et al. 2020), bycatch data from the Gulfarium C.A.R.E. Center, based on stranded individuals rescued for veterinary care, indicates that recreational bycatch at NP has grown since 2015 (Howell et al. 2021, Gulfarium C.A.R.E. Center unpubl. data, STSSN unpubl. data). From 2015 to 2016, NP averaged 7.5 sea turtles incidentally captured yr^{-1}, but from 2017 to 2020, NP averaged 35 sea turtles incidentally captured yr^{-1}, which is nearly a 500% increase (Gulfarium C.A.R.E. Center unpubl. data, STSSN unpubl. data). The bycatch is likely even higher than documented, as hooked sea turtles are not always reported by fishermen or able to be successfully rescued by stranding teams, in which case they would not be included in the STSSN database (Cook et al. 2020). Recreational bycatch occurs variably across FL GoMx fishing piers, which suggests that among other variables, environmental factors may influence bycatch. However, all of these factors are not well understood, nor are the potential impacts of recreational bycatch on sea turtle population recovery.

Other factors, such as reporting effort, can also influence recreational bycatch rates across FL GoMx fishing piers. Unlike commercial fisheries, which are observed by trained individuals who document bycatch of imperiled species, recreational fisheries are largely reliant on self-reporting of bycatch from fishermen (Cook et al. 2020). Many FL fishing piers along the GoMx, including NP, are part of the Responsible Pier Initiative (RPI), which promotes education and outreach at piers to encourage responsible fishing and proper reporting (https://marinelife.org/conservation/shield/responsible-pier-initiative/, Plotkin & Pena 2014). Fishing piers associated with the RPI display signage regarding dangerous interactions between fishermen and wildlife, including what to do if you hook a sea turtle (https://marinelife.org/conservation/shield/responsible-pier-initiative/, Plotkin & Pena 2014). Greater outreach has been shown to increase awareness, and it could increase reporting of bycatch; therefore, the site's sea turtle recreational bycatch rates can also be influenced by awareness of the parties involved (Cook et al. 2020).

The reported sea turtles that are incidentally captured are often taken to local rehabilitation facilities for hook removal and an overall health assessment before being released (FWC 2016). While fishing bait may directly attract sea turtles to fishing piers, especially for Kemp's ridley and loggerhead sea turtles, which are both carnivorous, it is surprising that green sea turtles, nominally herbivores, are frequently incidentally captured at some piers. However, juvenile green sea turtles can be omnivorous,

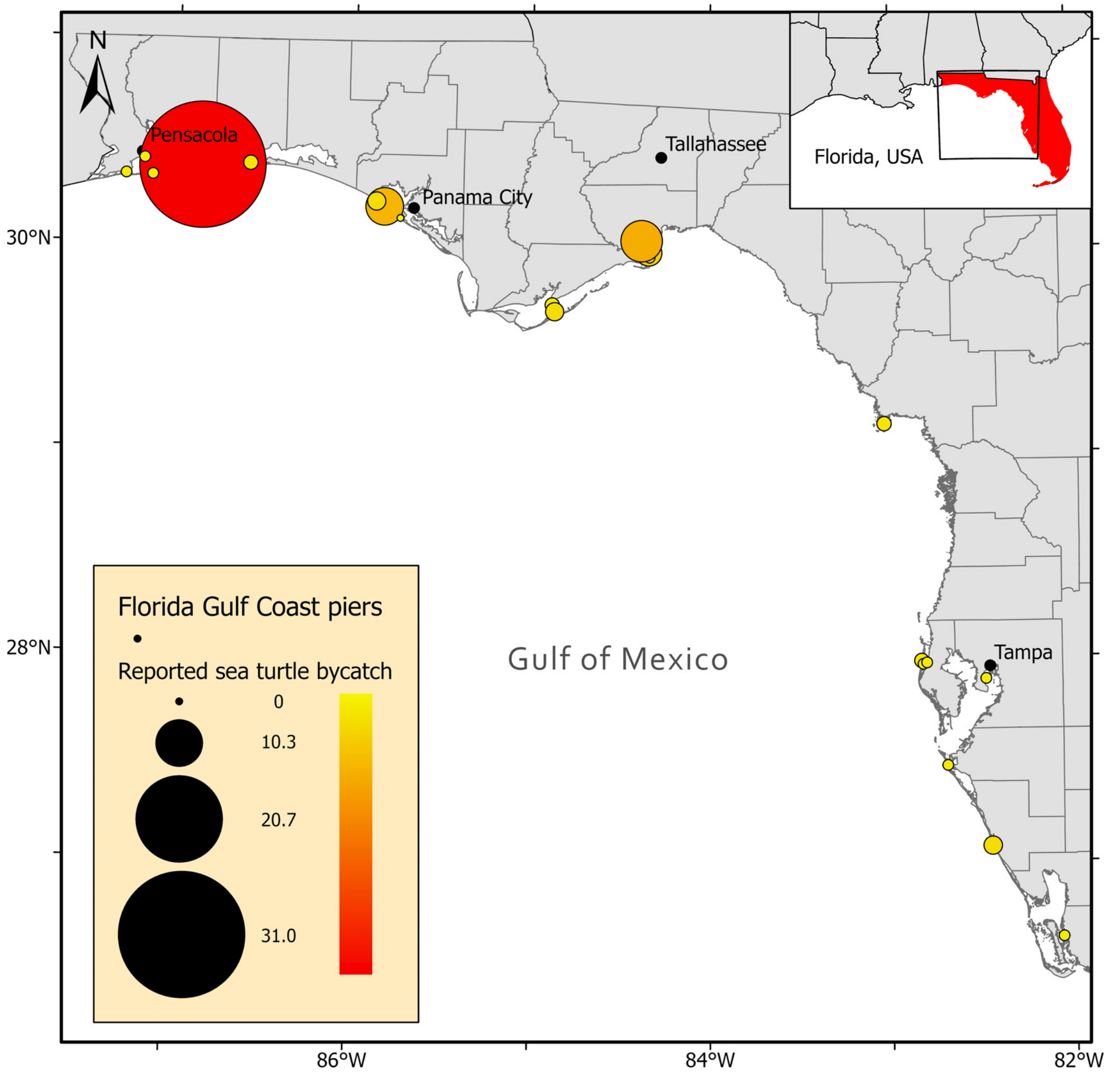

Fig. 1. Distribution of reported recreational sea turtle bycatch from 2015 to 2017 (Sea Turtle Stranding and Salvage Network) at Florida fishing piers located on the Gulf of Mexico

though most reports suggest that invertebrates are usually ingested, not fish, but it is possible that juveniles could be attracted to fishing bait (Nagaoka et al. 2012, Williams et al. 2014, Howell & Shaver 2021). Moreover, many rescued sea turtles at fishing piers are foul-hooked, where the hook is caught on some body part other than the mouth, which suggests that sea turtles could either not be targeting bait when incidentally captured or become foul-hooked accidentally before ingesting bait (Gulfarium C.A.R.E. Center unpubl. data, STSSN unpubl. data). From 2015 to 2020, 179 sea turtles arrived at Gulfarium C.A.R.E Center from fishing piers (Gulfarium C.A.R.E. Center unpubl. data). Most sea turtles had fishing gear (i.e. hooks or fishing line) attached or entangled around their body (76%), and many sea turtles were rescued with hooks in their mouths or gastrointestinal tracts (52%) (Gulfarium C.A.R.E. Center unpubl. data). Sea turtles observed with numerous hooks within the gastrointestinal tract would suggest evasion from previous hook-and-line bycatch incidents. Anecdotally, some sea turtles that arrive at Gulfarium after being hooked at fishing piers show signs of declining health (increased epibiont load, sluggish movements, and lack of appetite). It is possible that sea turtles with declining health feed around fishing piers due to the decreased energetic investment required to feed when compared to natural foraging habitats in the area. Perhaps fishing pier bycatch is a multidimensional problem more complex than depredation, as sea turtles are hooked externally at such a high rate, reported sea turtle bycatch of each species does not occur equally across all of FL GoMx fishing piers, and some sea turtles observed and rescued at fishing piers display signs of declining health.

While bait may attract sea turtles to fishing piers, the environmental context of fishing piers may also drive bycatch patterns. Sea turtles frequently forage, nest, and traverse nearshore habitats in the GoMx (Lamont et al. 2015, Hart et al. 2018, Lamont & Johnson 2021, Lamont et al. 2021, Siegfried et al. 2021). Short distance foraging movements have been observed among sea turtles, suggesting the importance of foraging sites dense with resources (Lamont & Iverson 2018). Additionally, sea turtle movements during foraging are generally shorter than their movement during migrations (Song et al. 2002, Hart & Fujisaki 2010, MacDonald et al. 2013). Therefore, the proximity of piers to various habitats and the structural complexity of fishing piers likely attracts sea turtles to those piers and, as a result, can impact turtle bycatch (Fikes 2013, Holloway-Adkins & Hanisak 2017, Siegfried et al. 2021).

Current work on recreational sea turtle bycatch at fishing piers centers around the prevalence of its occurrence, social factors (e.g. fishing practices), behavioral selections for sea turtles inhabiting piers, and diet of the sea turtles incidentally captured (Canon et al. 1994, Rudloe & Rudloe 2005, Seney 2008, 2016, Coleman et al. 2016, Cook et al. 2020, Lamont et al. 2021, Rose et al. 2022). Here, we investigated potential predictors of sea turtle recreational bycatch at FL GoMx fishing piers by conducting spatial analysis in ArcGIS to determine the relationship between environmental variables and recreational bycatch. These results can be used to inform management plans to reduce harmful interactions with sea turtles at fishing piers.

2. MATERIALS AND METHODS

2.1. ArcGIS data collection

We obtained data on stranded sea turtles from the FL STSSN from 2015 to 2017 to create a record of GPS coordinates for 21 FL fishing piers along the GoMx with reported bycatch (https://www.fisheries.noaa.gov/national/marine-life-distress/sea-turtle-stranding-and-salvage-network, STSSN unpubl. data). We also collated GIS spatial maps of artificial reefs (FWC 2020a), seagrass beds (FWC 2020b), bathymetry (200 m isobath, FGDL 2002), preserved waters (state-owned submerged land that has been set aside due to increased ecological, scientific, esthetic significance, FDEP 2011a), and outstanding waters (state surface waters that were set aside to be protected from any further environmental degradation, FDEP 2011b), and sea turtle nesting density at index and state-monitored beaches (FWC 2020c) along the FL GoMx Coast, as these could be biologically relevant to influence sea turtle occupancy and bycatch at fishing piers. We used ArcGIS Pro (v.2.9.1) to visualize the spatial relationships between sea turtle bycatch and the pier's location in FL.

Using the *measure* function in ArcGIS, we measured the distance to the coastal shelf break (defined as the 200 m isobath, used as an indicator of productivity, Pondella et al. 2019), the distance to the nearest seagrass bed, and the distance to the nearest artificial reef by taking the straight-line distance across aquatic habitat for each of the FL GoMx piers. We used home range and core use area buffers surrounding the fishing piers to define zones of potential habitat within a sea turtle's movement range. We defined home range as the area sea turtles established for foraging and inhabited on a consistent basis (Makowski et al. 2006, Lamont et al. 2015, Lamont & Iverson 2018). We defined core use areas as the areas of the home range sea turtles preferentially occupied (Bingham & Noon 1997, Makowski et al. 2006, Lamont & Iverson 2018). Then, buffers for each pier were created based on existing satellite telemetry analysis of 3 sea turtle species (green, loggerhead, and Kemp's ridley) in the northern GoMx (Lamont & Iverson 2018). Since green and loggerhead sea turtles were the species primarily incidentally captured, the buffers were adapted from the core use area (17.2 km^2) and home range (70.8 km^2) estimates reported in Lamont & Iverson (2018). However, we doubled the area estimates reported in Lamont & Iverson (2018) for home range and core use area to allow for uncertainty in the location of the center of the sea turtles' home range and core use areas.

We then ascertained the area of seagrass beds, area of preserved water, area of outstanding water, tonnage of artificial reef, area of conserved land (mostly undeveloped property that retained its natural condition and was managed with a commitment to preserve the natural state, https://www.fnai.org/conslands/conservation-faq), and length of conserved nesting shoreline (sea turtle nesting coastline that fell within an area of conservation land), within a turtle's estimated core use area and home range buffers of the pier (data for global model variables are available in Table A1 in the Appendix). The seagrass beds that fell within the home range and core use area buffers were converted into separate layers using the *intersect* and *clip* tools in ArcGIS. The area of those clips was calculated using the *calculate shape geometry* function. We used the *selection by location* function to examine the seagrass beds within the core use area and home range buffers for each pier. The total area was calculated by summing the area from each seagrass bed within the home range and core use area buffers of the piers. The same methodology was used to calculate the area of preserved water, conserved water, conserved land, and length of conserved nesting shoreline. A layer of conserved nesting shoreline was created by clipping a FL nesting shoreline layer where it fell within the conserved lands layer.

The tonnage of artificial reefs within the buffers was calculated by using the *select by location* feature for each pier's home range and core use area buffers to select the artificial reefs within proximity of each pier. Since tonnage of artificial reef was an attribute of the layer, the tonnage was summed for each individual pier's selection. Tonnage served as a more functional measure for the amount of artificial reef since artificial reefs usually represent a discrete point rather than a broad area like seagrass beds. Depending on the material used, amount deployed, area, and the depth variation that occurs at these sites, the reef could have a vastly different environmental footprint. The measurement of tonnage allowed us to better estimate the amount of potential habitat and 3D structure present at each of these discrete reef sites.

The density of sea turtle nesting at the nearest index beach and state-monitored beach was calculated by averaging sea turtle nests for each beach. Some piers were not located within a reasonable proximity of a nesting beach, so the nesting density for those piers was recorded as 0 (see Table 1). We included this variable as it is plausible that areas with higher average nesting effort would have more sea turtles transiting towards the nesting beaches, at least during the nesting season (nominally May 1 to October 31), which, in turn, could then increase the chance of bycatch. The average nesting effort was then divided by the length (km) of the beach to determine the nesting density (avg. sea turtle nests km^{-1}).

2.2. Data analysis and model selection

We statistically analyzed environmental correlates of sea turtle bycatch (following Zuur et al. 2009). Exploratory plots of model residuals for each variable were examined and used to evaluate if outliers had undue influence on the model results. From this, we identified Bradenton Fishing Pier as an outlier and removed it from the dataset. The estimated tonnage of artificial reef within its home range buffer was ~20× greater than the next closest pier. The artificial reefs near Bradenton Pier were unusual because >30 000 US tons of limestone rubble were dropped across 2 artificial reef sites, while most other artificial reefs were composed of concrete reef modules and other concrete structures (FWC 2020a). Following the removal of Bradenton Pier, variables with high variance inflation factors were removed to prevent having variables that were collinear (see our Table A1 for full list of variables collected; Zuur et al. 2009). After removing variables with high variance inflation factors, 8 variables remained in the global model for each response variable, total sea turtle bycatch, combined loggerhead and Kemp's ridley sea turtle bycatch, and green sea turtle bycatch. The global model for total sea turtle bycatch was

$$\text{Total sea turtle bycatch} = \beta_0 + \beta_1 \times \text{DistShelfBrk} + \beta_2 \times \text{DistSeagrs} + \beta_3 \times \text{Lat} + \beta_4 \times \text{PreWatCA} + \beta_5 \times \text{TonArtReefCA} + \beta_6 \times \text{ConShCA} + \beta_7 \times \text{TonArtReefHR} + \beta_8 \times \text{NestDensIB} + \varepsilon_i \tag{1}$$

DistShelfBrk is the distance to shelf break (200 m isobath), DistSeagrs is the distance to the nearest seagrass bed, Lat is the latitude of the pier, PreWatCA is the area of preserved water in the core use area buffer, TonArtReefCA is the tonnage of artificial reef in the core use area buffer, ConShCA is the length of conserved nesting shoreline in the core use area, TonArtReefHR is the tonnage of artificial reef in the home range buffer, NestDensIB is the nesting density at the nearest index beach, β_0 is the intercept, and ε_i ~$N(0, \sigma^2)$ of site *i*. Since loggerhead and Kemp's ridley sea turtles exhibit different foraging ecology compared to green sea turtles, and loggerheads and Kemp's ridley sea turtles exhibit similar foraging strategies, we also evaluated relationships specifically for combined loggerhead and Kemp's ridley sea turtles and separately for green sea turtles.

$$\text{Loggerhead and Kemp's ridley sea turtle bycatch} = \beta_0 + \beta_1 \times \text{DistShelfBrk} + \beta_2 \times \text{DistSeagrs} + \beta_3 \times \text{Lat} + \beta_4 \times \text{PreWatCA} + \beta_5 \times \text{TonArtReefCA} + \beta_6 \times \text{ConShCA} + \beta_7 \times \text{TonArtReefHR} + \beta_8 \times \text{NestDensIB} + \varepsilon_i \tag{2}$$

$$\text{Green sea turtle bycatch} = \beta_0 + \beta_1 \times \text{DistShelfBrk} + \beta_2 \times \text{DistSeagrs} + \beta_3 \times \text{Lat} + \beta_4 \times \text{PreWatCA} + \beta_5 \times \text{TonArtReefCA} + \beta_6 \times \text{ConShCA} + \beta_7 \times \text{TonArtReefHR} + \beta_8 \times \text{NestDensIB} + \varepsilon_i \tag{3}$$

Due to the small sample size of fishing piers, candidate models were limited to a maximum of 3 explanatory variables. We used the information-theoretic approach with the Akaike information criterion correction for small sample sizes (AICc, Akaike 1974, Anderson & Burnham 2002). The initial diagnostic plots suggested the residuals of a linear regression were heteroscedastic and non-normally distributed; therefore, we used generalized additive models (GAMs). We performed model selection using the *dredge* function in the MuMIN package in R v.4.0.0 (R Development Core Team, 2021) and RStudio v.1.2.5042 (RStudio Team 2021). This approach evaluated which of the collected environmental factors were most influential in determining total sea turtle bycatch, green sea turtle bycatch, and combined loggerhead and Kemp's ridley sea turtle bycatch across all FL GoMx piers.

3. RESULTS

3.1. Fishing pier bycatch and environmental predictors

Recreational bycatch varied across the 20 fishing piers (3.95 ± 6.79 sea turtles incidentally captured, mean ± SD; Table 1). From 2015 to 2017, green (straight carapace length [SCL]: 37.4 ± 7.6 cm, mean ± SD, n = 26), loggerhead (70.7 ± 6.5 cm, n = 13), and Kemp's ridley (33.1 ± 7.2 cm, n = 30) sea turtles were incidentally captured at 20 FL fishing piers along the GoMx. Notably, only 69 of the 80 turtles reported in STSSN data had a reported SCL. The environmental predictors varied across fishing piers (Table 1). For example, the average (±SD) amount of artificial reef within the home range buffer was 236 ± 419 US tons, whereas the length of conserved nesting shoreline within the core use area buffer averaged 0.41 ± 0.76 km.

3.2. Modeling recreational sea turtle bycatch

3.2.1. Total sea turtle bycatch

The model confidence set for total sea turtle bycatch, using a GAM, in-

Table 1. Data for reported recreational sea turtle bycatch and environmental variables at Florida Gulf of Mexico fishing piers. CM: green sea turtle *Chelonia mydas*; CC: loggerhead sea turtle *Caretta caretta*; and LK: Kemp's ridley sea turtle *Lepidochelys kempii*. For other abbreviations, see Table A1 in the Appendix

Fishing pier	Bycatch 2015–2017				DistShelfBrk (km)	DistSeagrs (km)	Lat (DD)	PreWatCA (km^2)	TonArtReefCA (US tons)	ConShCA (km)	TonArtReefHR (US tons)	NestDensIB (km^{-1})
	CM	**CC**	**LK**	**Total**								
Navarre Beach Fishing Pier	25	6	0	31	70.56	34.38	30.38	0	27	1.91	1547	1.43
M.B. Miller County Pier	0	6	2	8	100.13	12.99	30.19	0	0	0	0	1.15
Venice Sharky's Pier	0	3	0	3	204.38	5.12	27.07	0	0	0.15	0	42.53
Pensacola Beach Fishing Pier	0	0	1	1	63.80	18.36	30.33	0	0	0.04	607.7	1.43
Pier 60 Clearwater	0	0	3	3	185.93	2.01	27.98	5.96	481	0	681	10.01
Mashes Sands Beach Pier	0	0	5	5	186.65	0.47	29.97	0	0	0	0	0
Eastpoint Pier	0	0	2	2	125.97	1.30	29.71	3.90	0	0	0	8.10
Russell Fields Pier	2	1	0	3	100.27	18.21	30.21	0	0	0	0	1.15
Sand Key Fishing Pier	1	0	0	1	186.67	0	27.96	7.03	200	0	681	10.01
Okaloosa Island Fishing Pier	1	1	0	2	79.64	8.43	30.39	0	138	0.77	727	1.43
Bradenton Beach City Pier[a]	1	0	0	1	196.86	0.03	27.47	0	0	0	30181	10.01
Bald Point State Park Pier	0	0	1	1	184.22	0.33	29.95	0	0	1.21	0	0
Ballast Point Park Pier	0	0	1	1	235.92	0.16	27.89	0	0	0	0	10.01
Cedar Key Municipal Pier	0	0	2	2	217.30	7.88	29.13	4.61	0	0	0	0
St. George Island Fishing Pier	0	0	3	3	124.17	1.30	29.68	4.12	0	0	0	8.10
Woolley Park Pier	0	0	9	9	194.53	0.23	30.03	0	0	0	0	8.10
Pensacola Bay Fishing Bridge	0	0	1	1	82.30	1.08	30.41	0	0	0	0	1.43
Matlacha Community Park Pier	0	0	1	1	237.51	0.01	26.63	4.84	0	0	0	3.51
Clearwater Harbor Docks	0	0	1	1	188.53	0.01	27.97	4.00	0	0	481	10.01
Fort Pickens Pier	0	1	0	1	69.22	1.60	30.33	2.69	0	2.40	0	1.43
St. Andrews State Park Pier	0	0	0	0	102.65	2.39	30.13	3.96	0	1.69	0	1.15
Total	**30**	**18**	**32**	**80**								

[a]Bradenton Beach City Pier was removed from the statistical analysis due to an outlying value for TonArtReefHR, which caused undue influence on the model

cluded 4 models with 4 different environmental variables: artificial reef tonnage in the home range buffer, length of conserved nesting shoreline in the core use area, preserved waters in the core use area, and latitude (see Table A2 in the Appendix). Artificial reef tonnage within the home range buffer was present in all the top models for total sea turtle bycatch, and artificial reef tonnage was positively related to total sea turtle bycatch, though the relationship was not linear (Fig. 2A). The length of conserved nesting shoreline within the core use area buffer was featured in 2 of the models and catch tended to increase, where conserved nesting shoreline was greater, though, again, this relationship was nonlinear (see Appendix, Fig. 2B). Preserved water in the core use area buffer and latitude of the pier were present in one of the top ranked models, but the models with these variables reported AICc weights of 0.165 and 0.138, respectively, suggesting their importance as predictors of sea turtle bycatch was lower (see Appendix, Fig. 2C,D).

3.2.2. Loggerhead and Kemp's ridley sea turtle bycatch

The confidence set for combined loggerhead and Kemp's ridley sea turtle bycatch featured 5 top-ranked models consisting of 4 different variables: area of preserved water within the home range buffer, distance to nearest seagrass bed, tonnage of artificial reef within the home range buffer, and latitude of pier (Table 2). None of the 4 variables was

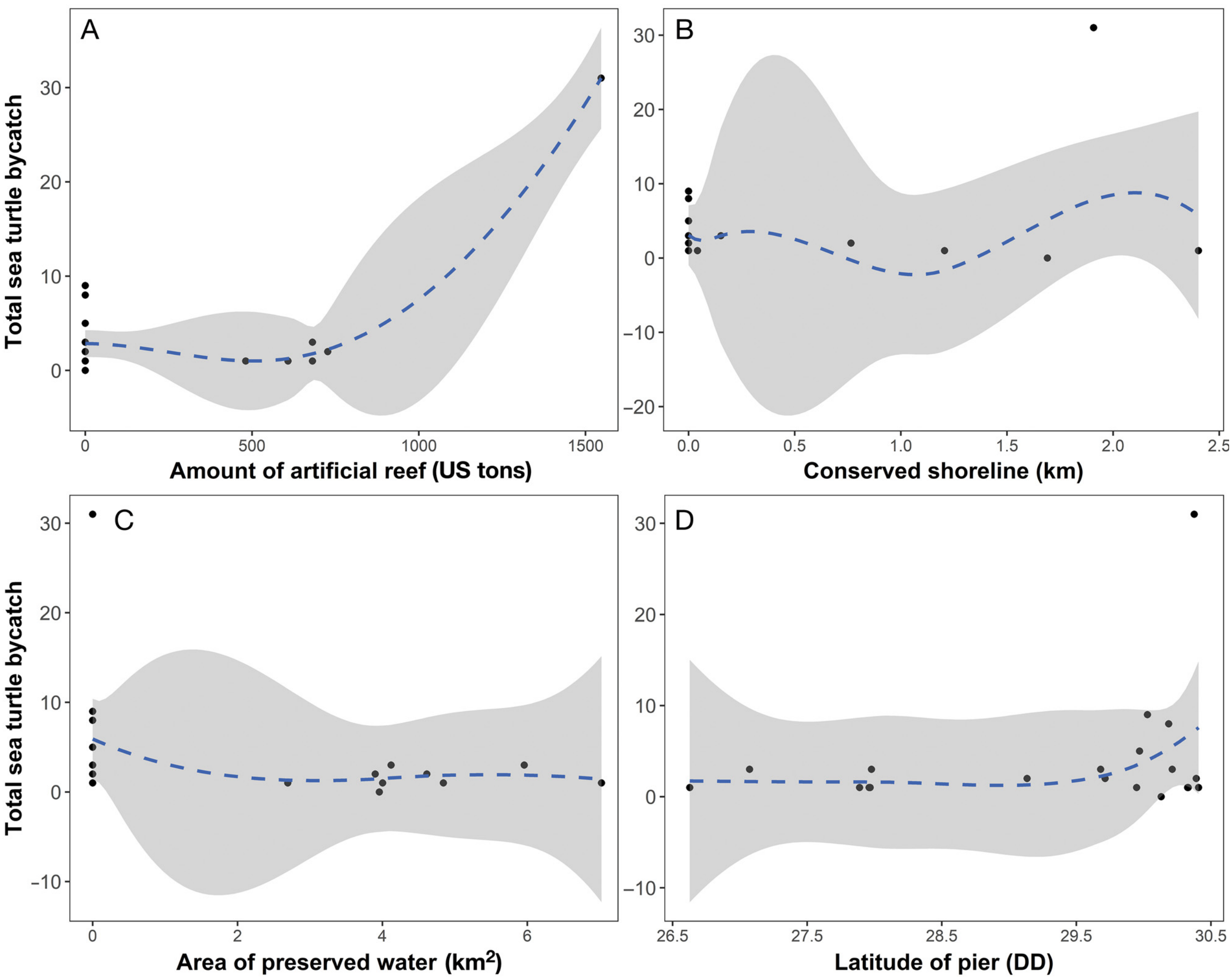

Fig. 2. Generalized additive models of total sea turtle bycatch and each of the explanatory variables present in the confidence set: (A) amount of artificial reef; (B) conserved shoreline; (C) area of preserved water; (D) latitude of pier. Black dots: observed bycatch and measured environmental variable; dashed lines: predicted fit; shading: 95% CI. DD: decimal degrees. Note the different *y*-axis scales

Table 2. Confidence set of models (ΔAICc < 2) for estimating loggerhead and Kemp's ridley sea turtle bycatch and green sea turtle bycatch at Florida Gulf of Mexico fishing piers using environmental data. (+) Variable was included in the model; (–) variable was not included in the model; AICc: Akaike's information criterion corrected for small sample size; ΔAICc: difference in AICc from the top-ranked model; R.I.: relative importance of variable. For other abbreviations, see Table A1 in the Appendix

	Model terms								Model support			
	DistShelf Brk	DistSea grs	Lat	PreWat CA	TonArt ReefCA	ConSh CA	TonArt ReefHR	NestDens IB	df	AICc	ΔAICc	AICc weight
Loggerhead and Kemp's ridley sea turtle bycatch												
Model 1	–	–	–	+	–	–	–	–	3	98.05	0	0.30
Model 2	–	–	–	–	–	–	–	–	2	98.12	0.06	0.29
Model 3	–	+	–	–	–	–	–	–	3	99.45	1.40	0.15
Model 4	–	–	–	–	–	–	+	–	3	99.71	1.66	0.13
Model 5	–	–	+	–	–	–	–	–	3	99.80	1.75	0.13
R.I.	–	0.150	0.125	0.301	–	–	0.132	–				
Green sea turtle bycatch												
Model 1	–	+	–	–	–	–	+	–	5	34.41	0	1

present in >1 of the top-ranked models, and one of the top ranked models featured none of the variables present in the global model (Table 2). The highest-ranking model featured area of preserved water within the home range buffer, which displayed a negative but nonlinear relationship with loggerhead and Kemp's ridley bycatch (Fig. 3A). The second highest featured none of the variables present in the global model. The next highest ranking models featured distance to nearest seagrass bed (Fig. 3B), tonnage of artificial reef within the home range buffer (Fig. 3C), and latitude of pier (Fig. 3D), with all variables displaying a nonlinear relationship with loggerhead and Kemp's ridley sea turtle bycatch; the AICc weights for each of the models featuring these variables was 0.150, 0.132, and 0.125, respectively, indicating the importance of these predictors to loggerhead and Kemp's ridley bycatch was lower than the top-ranked model featuring the area of preserved water in the home range buffer (Table 2).

3.2.3. Green sea turtle bycatch

The confidence set for green sea turtle bycatch featured one top-ranked model, consisting of distance to nearest seagrass bed and tonnage of artificial reef within the home range buffer (Table 2). Both distance to nearest seagrass bed (Fig. 4A) and tonnage of artificial reef (Fig. 4B) exhibited a positive relationship with green sea turtle bycatch. Notably, NP drives the relationships observed between bycatch and the environmental variables because of its unusually high green sea turtle bycatch and high values for artificial reef tonnage, distance to nearest seagrass bed, and conserved nesting shoreline.

4. DISCUSSION

The GAM selection analysis indicated that the tonnage of artificial reef within a home range buffer, length of conserved nesting shoreline within a core use area buffer, latitude of pier, and preserved water within a core use area buffer are all potential predictors of total sea turtle bycatch at fishing piers along the FL GoMx coast. Higher tonnage of artificial reef was positively related to increased green sea turtle bycatch. The relationship between green sea turtle bycatch and tonnage of artificial reef suggests that high densities of artificial reefs could attract green sea turtles and make them more susceptible to recreational bycatch at nearby fishing piers. On the other hand, tonnage of artificial reef and the combined loggerhead and Kemp's ridley sea turtle bycatch appear to be related as well; however, these factors have a nonlinear relationship. The relationship between the combined bycatch of loggerhead and Kemp's ridley sea turtles and tonnage of artificial reefs suggests that the presence of artificial reef influences combined loggerhead and Kemp's ridley sea turtle bycatch, though the relationship between these factors is less clear than the one observed between tonnage of artificial reef and green sea turtle bycatch.

The proximity of artificial reefs to fishing piers means that the sea turtles frequenting the reefs could easily travel between the reefs and the piers, and

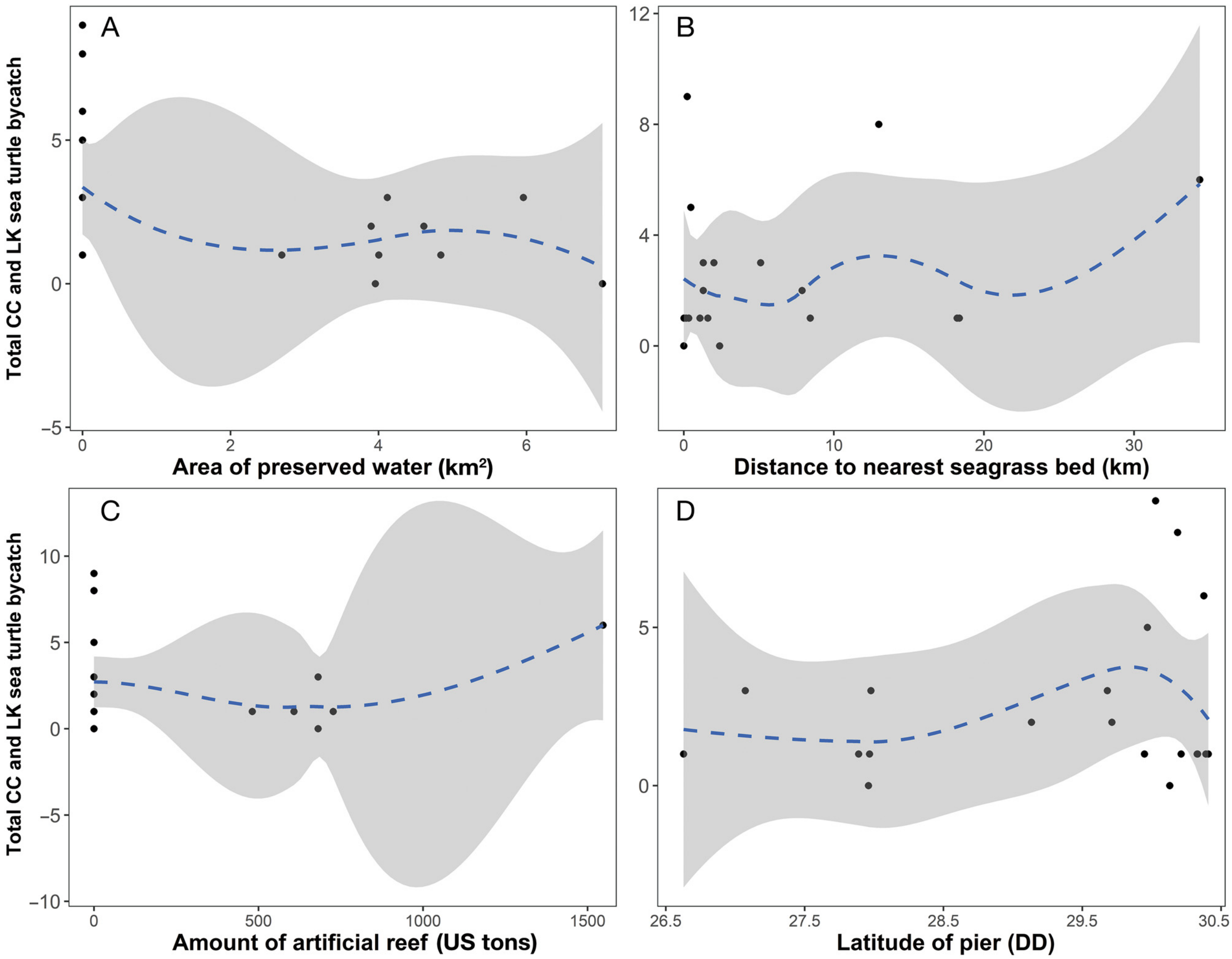

Fig. 3. Generalized additive models of loggerhead (CC: *Caretta caretta*) and Kemp's ridley (LK: *Lepidochelys kempii*) sea turtle bycatch and each of the explanatory variables present in the confidence set: (A) area of preserved water; (B) distance to nearest seagrass bed; (C) amount of artificial reef; (D) latitude of pier. Black dots: observed bycatch and measured environmental variable; dashed lines: predicted fit; shading: 95% CI. DD: decimal degrees. Note the different *y*-axis scales

then opportunistically interact with fishing gear and become incidentally captured. The FL GoMx coastal shelf, and generally throughout the GoMx, is relatively devoid of natural, hard structures for habitat (Dufrene 2005, Gallaway et al. 2009). Further, the nearshore benthos is primarily sandy bottom, and offshore shelf habitats have low seagrass coverage, especially in the northern GoMx, west of Apalachee Bay (Dufrene 2005, FWC 2020b). Therefore, the artificial reefs could serve as an oasis of resources within a mostly resource-deficient natural environment for sea turtles to aggregate (Streich 2016).

To improve conservation of imperiled species, researchers often seek conservation of critical natural foraging habitats, especially those supporting multiple species (Hart et al. 2018). While conservation of critical natural habitats is instrumental to sea turtle conservation, protections and fisheries limitations or conservation buffers for artificial habitats frequented by sea turtles could also present benefits; however, further research needs to be conducted to better understand the role of artificial habitats for sea turtles (Carr & Hixon 1997, Feary et al. 2011, Hart et al. 2018). The occupancy rates and use of FL GoMx artificial reefs by sea turtles are not fully documented. However, recent work suggests that nearshore artificial reefs in northwest FL are inhabited by the same species as those incidentally captured at the fishing piers (Siegfried et al. 2021). Due to the resources present at artificial reefs compared to the surrounding natural habitat, the artificial reefs could be serving as a more critical offshore and nearshore habitat for sea turtles than expected (Carr & Hixon 1997, Feary et al. 2011). The bycatch rates at piers

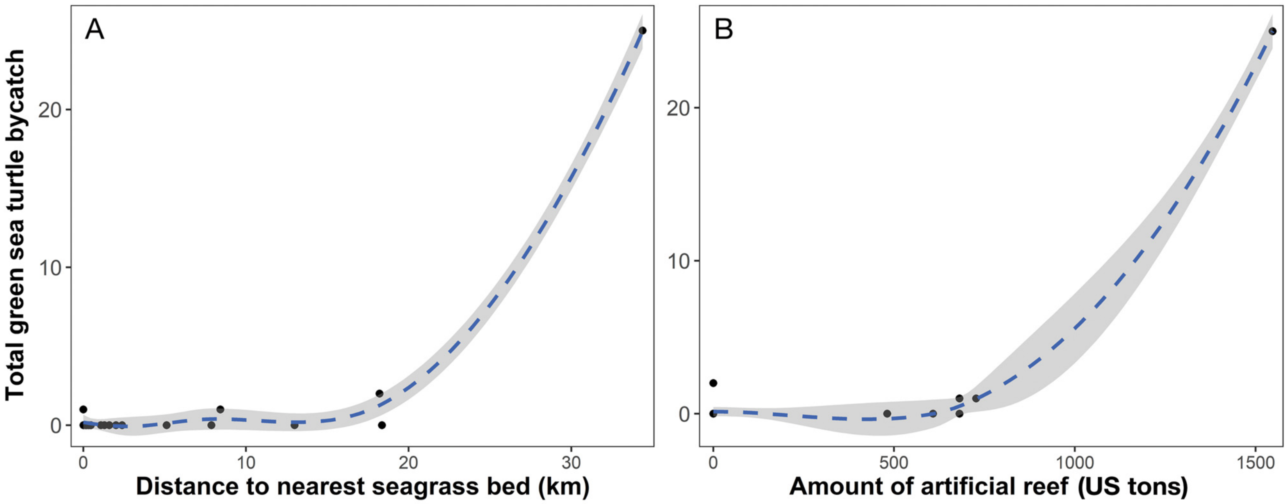

Fig. 4. Generalized additive models of green sea turtle bycatch and each of the explanatory variables present in the confidence set: (A) distance to nearest seagrass bed; (B) amount of artificial reef. Black dots: observed bycatch and measured environmental variable; dashed lines: predicted fit; shading: 95% CI

adjacent to large deployments of artificial reefs could be influenced by a higher-than-normal aggregation of sea turtles at artificial reefs compared to natural sandy bottom habitat. Since very little research is directed at sea turtles utilizing artificial habitats compared to natural habitats or dynamic use across them, it is difficult to contextualize our results here (but see Coyne 1994, Metz & Landry 2013, Gorham et al. 2014, Barnette 2017, Siegfried et al. 2021). In all, more research directed at sea turtle use of artificial habitats would help to clarify these patterns.

Deployment of artificial reefs in close proximity to heavily trafficked and easily accessible fishing locations (i.e. fishing piers and docks) can have negative conservation implications for imperiled species that frequent them. The potential risk for recreational bycatch of these species suggests greater consideration should be taken when determining the type, amount, and location of artificial reefs being deployed (Pears & Williams 2005). Additionally, artificial reefs are intended to supplement and restore degraded natural habitat; however, using artificial reefs to provide habitat in a location without natural structure could alter aggregations of various organisms, including imperiled species (Seaman 2007, Feary et al. 2011). Artificial reefs can also function as positive novel habitats that support the recovery of over-harvested and endangered species (Claisse et al. 2014). Further research into the trade-offs and functioning of artificial habitats in an ecosystem context would help to resolve this.

The length of conserved nesting shoreline, area of preserved water, and latitude of piers are probably less important predictors of sea turtle bycatch, as they do not occur in all the models in the confidence sets for total sea turtle bycatch or combined loggerhead and Kemp's ridley sea turtle bycatch. These variables are likely indirect measures of habitat quality; further, these predictors may be proxies for other factors that directly relate to bycatch. For example, decreased anthropogenic effects associated with stretches of conserved nesting shoreline and preserved waters could promote indirect positive environmental effects, which ultimately improves the ecological condition of nearshore habitats. As a result, these areas could have increased sea turtle occupancy (Scyphers et al. 2015, Bilkovic et al. 2016). Conserved nesting shorelines and preserved waters can be analogous to marine protected areas (MPAs), which increase productivity and enhance the stability of marine ecosystems (Tissot et al. 2004, Fraschetti et al. 2013). Additionally, there could be ecological spillover of marine organisms from preserved waters adjacent to piers, which has been observed between MPAs and neighboring waters (Di Lorenzo et al. 2016). Further evaluation of these variables and their influence on sea turtle presence will need to be conducted to elucidate the significance of these impacts.

Distance to the nearest seagrass bed was not present in any of the top models for overall sea turtle bycatch, but it was present in the top model for green sea turtle bycatch and one of the top models for combined loggerhead and Kemp's ridley sea turtle bycatch. It is somewhat surprising that distance to the nearest seagrass bed appears in a top model for loggerhead and Kemp's ridley sea turtle bycatch.

The relationship between distance to nearest seagrass bed and loggerhead and Kemp's ridley sea turtle bycatch was nonlinear, with no consistent relationship. Therefore, for the loggerhead and Kemp's ridley sea turtle bycatch model, distance to the nearest seagrass bed could be serving as a proxy for another variable not included in the set. For example, oftentimes, the closest seagrass bed was located in sheltered bodies of water (i.e. sound, bay, etc.) within proximity of the pier, so in many cases, the distance to the nearest seagrass bed also indirectly measured the distance to estuaries which contain prey items of loggerhead and Kemp's ridley sea turtles, like decapods and fish (Plotkin et al. 1993, Schmid et al. 2003). Further, loggerheads and Kemp's ridley sea turtles have been known to inhabit estuaries along the northern GoMx (Seney & Landry 2011, Lamont & Iverson 2018). Though these species have been observed in the same bodies of water, loggerhead and Kemp's ridley sea turtles may not be occupying the same habitats or areas within that body of water. For example, loggerhead and Kemp's ridley sea turtles have been observed partitioning habitat in the Chesapeake Bay (DiMatteo et al. 2022). Loggerhead sea turtles were observed more frequently in deeper portions of the Chesapeake Bay than Kemp's ridley sea turtles and at intermediate depths (12–48 m) along the coastal shelf of the eastern GoMx (Griffin & Griffin 2003, Schmid et al. 2003, DiMatteo et al. 2022). Even niche-partitioning of a single artificial structure by green, loggerhead, and Kemp's ridley sea turtles has been observed in St. Joseph Bay, FL (Lamont et al. 2022). Evidence of habitat partitioning further complicates models combining both loggerhead and Kemp's ridley sea turtles, because it creates potential for regional specificity of habitat use along the eastern GoMx. Further, this suggests that different sea turtle species could inhabit different portions of these piers and indicates that different factors can influence loggerheads and Kemp's ridley sea turtle bycatch despite their similar prey items.

The nonlinear relationship of distance to the seagrass bed and loggerhead and Kemp's bycatch also suggests that there may be better predictors of combined loggerhead and Kemp's ridley sea turtle bycatch than the distance to nearest seagrass bed. Kemp's ridley sea turtles in the eastern GoMx have been observed preferentially occupying hard substrates, which are known to have common prey items, like blue crabs and stone crabs, over habitats like seagrass beds and oyster reefs (Schmid et al. 2003). Perhaps the surrounding context of hard substrate for piers located within FL estuaries is more complex than the documented deployments of artificial reefs, or the pier itself is providing enough hard substrate to attract loggerhead and Kemp's ridley sea turtles. Further investigation of the surrounding benthos for FL GoMx fishing piers could give added context to different results observed for loggerhead and Kemp's ridley sea turtle bycatch.

On the other hand, the relationship between the distance to the nearest seagrass bed and green sea turtle bycatch shows a strong positive relationship; in other words, green sea turtle bycatch increases the farther away the piers are from the seagrass habitat (Fig. 4). It is not surprising that the distance to nearest seagrass bed appeared in the top model for green sea turtle bycatch. Seagrass represents an important foraging resource for green sea turtles, unlike other sea turtle species inhabiting the northern GoMx (Howell et al. 2016, Howell & Shaver 2021).

The distance of seagrass beds to NP is particularly relevant, given its high juvenile green sea turtle bycatch. Further, NP has the greatest distance to nearest seagrass bed of the 20 FL fishing piers investigated (Table 1). Since no seagrass beds were present in the NP core use area or home range buffer, resident juvenile green sea turtles could be occupying piers and other artificial habitat in the northern GoMx as a transitional habitat before they undergo a strict ontogenetic shift in their diet. Juvenile green sea turtles tend to have greater plasticity in their diet than their adult counterparts (Howell et al. 2016). For example, juvenile green sea turtles were observed utilizing rock jetties adjacent to Padre Island and South Padre Island in Texas (Coyne 1994, Metz & Landry 2013).

Other juvenile green sea turtles who occupy NP could be reliant on the pier and adjacent artificial reef for temporary resting and foraging sites while traversing the coast to other foraging habitats. The distance between Choctawhatchee Bay and Pensacola Bay, 2 potential foraging areas around NP, is roughly 77 km. If juvenile green sea turtles are residing at NP, even temporarily, they may not be willing to travel beyond their home range centered around the pier. Indeed, the distance to Choctawhatchee Bay (~33.5 km) and Pensacola Bay (~43.5 km) both fall well outside the core use area and home range buffers (radius = 2.34 km and 4.75 km, respectively) for NP, which would represent a significant energetic cost to travel to either Choctawhatchee or Pensacola Bay from NP (Prange 1976). Additionally, resident green sea turtles might forego long-distance migrations between foraging and nesting habitats when an abundance of prey, potential mates, or refuge is available in a singular location (Carr 1980, Lamont et al. 2018). Further, long-distance migrations expose sea turtles to other stressors, like predators, limited and inconsistent food sources despite high energy output, and other bycatch risks and anthropogenic threats (Chan et al. 1988, Festa-Bianchet & Apollonio 2003, Lewison et al. 2004, Caretta et al. 2004, Benson et al. 2007, Alfaro-Shigueto et al. 2011, Jones et al. 2011).

Green sea turtles may be unwilling to expend the necessary energy required to travel to natural foraging grounds because their needs are being satisfied within proximity of the pier and the potential risks of travel are deemed too great (Carr 1980). For example, for a green sea turtle to travel to the nearest bay from NP, it would take nearly 22.5 h if the turtle were swimming at an average speed of 1.49 km h^{-1}; the journey would certainly require an extensive energetic investment (Prange 1976, Hart & Fujisaki 2010). Alternatively, the nearest offshore artificial reef would take roughly 1.25 h to travel to at that rate. The closer proximity of artificial habitat could provide a lower energetic cost and encourage greater occupancy of the fishing pier. Perhaps the combination of greater distance to the nearest seagrass bed and increased tonnage of artificial reef surrounding the pier contributes significantly to the rate green sea turtles are incidentally captured at fishing piers in the eastern GoMx.

Interestingly, 2 piers near NP have a significant amount of artificial reef within the home range buffer and a closer distance to the nearest seagrass bed, yet at these piers much lower sea turtle bycatch was observed than at NP (Okaloosa Island Fishing Pier: 2 reported sea turtles, Pensacola Beach Fishing Pier: 1 reported sea turtle). Further, piers with shorter distances to the nearest seagrass bed and little or no artificial reef adjacent the pier have moderate rates of reported sea turtle bycatch (i.e. M.B. Miller County Pier: 8 reported sea turtles, Mashes Sands Beach Pier: 5 reported sea turtles, and Woolley Park Pier: 9 reported sea turtles). However, it should be noted that no green sea turtles were incidentally captured at these piers. These results highlight the difficulty of modeling reported sea turtle bycatch with all 3 species together and supported the use of different models for green sea turtle bycatch and combined loggerhead and Kemp's ridley sea turtle bycatch. Factors that potentially influence green sea turtle bycatch do not appear to influence the combined bycatch of loggerheads and Kemp's ridley sea turtles. The model confidence set for combined loggerhead and Kemp's ridley included 4 distinct single-variable models and the intercept-only model (essentially the null model), which suggests lack of model agreement in the confidence set. Furthermore, as the null model is included in the confidence set (AICc weight = 0.29), we can't discount the possibility that none of the potential predictors are important for loggerhead and Kemp's ridley bycatch. It may be more likely that there are better predictors of recreational bycatch at fishing piers for these 2 species. More than likely, other variables, that we did not include, such as average salinity or area of habitat suitable for loggerhead and Kemp's ridley prey, would provide better insight into potential environmental drivers of recreational bycatch at fishing piers for these species. Better understanding of these potential predictors would provide critical conservation information to curb incidental capture of sea turtles at fishing piers, especially in areas where the prevalence of recreational bycatch of Kemp's ridley sea turtles is far greater.

Another potential concern is an increase in sea turtle occupancy at fishing piers. If closer proximity of artificial reef combined with a greater distance to the seagrass bed is contributing to increased potential occupancy of sea turtles at FL GoMx fishing piers, then this could pose serious concerns for green sea turtles residing at piers, as an increase in the density of sea turtles occupying a pier would likely increase their bycatch frequency. Additionally, as sea turtle populations recover, there will likely be greater abundance of sea turtles present in nearshore habitats, which would create increased potential for bycatch (Putman et al. 2020). Moreover, the rate of new artificial reef installations across the FL GoMx coast has increased dramatically since the *Deepwater Horizon* oil spill (https://myfwc.com/fishing/saltwater/artificial-reefs/). Continued monitoring of sea turtle residency near piers and documenting recreational bycatch at fishing piers, especially NP, can provide insight into green sea turtle usage of fishing piers. Further, satellite tagging or animal-borne cameras of individuals incidentally captured at sites can provide greater understanding of the home range and core use areas of resident and transient green sea turtles as well as behaviors that result in fair- and foul-hooking events at fishing piers (Lamont & Iverson 2018).

A longer-term dataset with a greater number of observations would allow for more refined models of sea turtle recreational bycatch at fishing piers along the FL GoMx coast. Currently, the conclusions drawn from the GAMs of green sea turtle, combined loggerhead and Kemp's ridley sea turtle, and total sea turtle bycatch are limited by the small sample size of reported sea turtle bycatch from 2015 to 2017. Specifically, the total sea turtle bycatch model is influenced by an abundance of green sea turtle bycatch at NP (n = 25), which greatly affects the model, and there was a lack of agreement across models in the confidence set for combined loggerhead and Kemp's ridley sea turtle bycatch. With a greater timeframe of data, the total sea turtle bycatch model and combined loggerhead and Kemp's ridley sea turtle bycatch models could be converted into 3 separate models for each species. Additionally, a greater timeframe could be used to identify a baseline sea turtle recreational bycatch rate to determine years and sites with unusually high bycatch, like the historical record of Kemp's ridley sea turtle bycatch at fishing piers along the Mississippi and Texas Gulf Coast (Canon et al. 1994, Rudloe & Rudloe 2005, Seney 2008, 2016, Coleman et al. 2016, Cook et al. 2020, Howell et al. 2021).

While environmental variables likely contribute to reported recreational sea turtle bycatch rates along the FL GoMx coast, education and awareness of fishermen and stakeholders certainly plays an important role as well. Thirteen of the 20 piers included in the model are members of the RPI; all 13 piers had joined the RPI by 2016, and the majority of piers (10) were members in 2015. Additionally, it is worth noting that the 4 piers with the greatest reported bycatch (NP, Woolley Park Fishing Pier, M.B. Miller County Pier, and Mashes Sands Beach Pier) are all members of the RPI (https://marinelife.org/conservation/shield/responsible-pier-initiative/). Formally studying these sites can also provide greater resolution for the variability in reported sea turtle bycatch across these sites (Cook et al. 2020).

5. CONCLUSION

Recreational sea turtle bycatch at fishing piers in the northern GoMx has been a primarily episodic issue (e.g. Kemp's ridley sea turtles at Mississippi piers), but currently it is increasing at fishing piers in northwest FL. The majority of the reported sea turtle bycatch along the FL GoMx has been concentrated at NP. Our analysis suggests that environmental variables associated with the broader ecological setting, i.e. artificial reef tonnage and distance to the nearest seagrass bed (for green sea turtles), can predict patterns of bycatch at fishing piers. Future plans for artificial reef deployment and fishing pier installation should consider the environmental context and impact to protected species of proposed sites to mitigate threats to sea turtles. Despite similarities between loggerhead and Kemp's ridley foraging items, the model of combined loggerhead and Kemp's ridley sea turtle bycatch had some limitations. An increased timeframe of recorded sea turtle bycatch at FL GoMx fishing piers and a more extensive examination of habitat context within estuaries would likely improve the combined loggerhead and Kemp's ridley sea turtle model and potentially allow for separate models for each species.

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Appendix

Table A1. Environmental variables collected remotely for modeling of sea turtle bycatch. FWC: Florida Fish and Wildlife Conservation Commission (FWC 2020a,b,c); FGDL: Florida Geographic Data Library (FGDL 2002); FNAI: Florida Natural Areas Inventory (Knight & FWC 2020, FNAI 2021); FDEP: Florida Department of Environmental Protection (FDEP 2011a,b); DD: decimal degrees

Environmental variable	Abbreviation	Unit	Data source
Distance to nearest artificial reef	DistArtReef	km	FWC
Distance to shelf break (200 m isobath)	DistShelfBrk	km	FGDL
Distance to nearest seagrass bed	DistSeagrs	km	FWC
Tonnage of artificial reef in core use area	TonArtReefCA	US tons	FWC
Tonnage of artificial reef in home range	TonArtReefHR	US tons	FWC
Length of conserved nesting shoreline in core use area	ConShCA	km	FWC, FNAI
Length of conserved nesting shoreline in home range	ConShHR	km	FWC, FNAI
Area of outstanding water in core use area	OutWatCA	km^2	FDEP
Area of outstanding water in home range	OutWatHR	km^2	FDEP
Area of preserved water in core use area	PreWatCA	km^2	FDEP
Area of preserved water in home range	PreWatHR	km^2	FDEP
Area of conserved land in core use area	ConLandCA	km^2	FNAI
Area of conserved land in home range	ConLandHR	km^2	FNAI
Area of seagrass in core use area	SeagrsCA	km^2	FWC
Area of seagrass in home range	SeagrsHR	km^2	FWC
Sea turtle nesting density at nearest index beach	NestDensIB	km^{-1}	FWC
Sea turtle nesting density at nearest state-monitored beach	NestDensSB	km^{-1}	FWC
Latitude of pier	Lat	DD	Collected
Longitude of pier	Long	DD	Collected

Table A2. Confidence set of models (ΔAICc < 2) for estimating total sea turtle bycatch at Florida Gulf of Mexico fishing piers using environmental data. (+) Variable was included in the model; (–) variable was not included in the model; AICc: Akaike's information criterion corrected for small sample size; ΔAICc: difference in AICc from the top-ranked model; R.I.: relative importance of variable. For other abbreviations, see Table A1

	Model terms								**Model support**			
	DistShelf Brk	DistSea grs	Lat	PreWat CA	TonArt ReefCA	ConShCA CA	TonArt ReefHR	NestDens IB	df	AICc	ΔAICc	AICc weight
Model 1	–	–	–	–	–	+	+	–	4	99.13	0	0.37
Model 2	–	–	–	–	–	–	+	–	3	99.33	0.20	0.33
Model 3	–	–	+	–	–	+	+	–	5	100.72	1.60	0.16
Model 4	–	–	–	+	–	–	+	–	4	101.09	1.96	0.14
R.I.	–	–	0.165	0.138	–	0.531	1	–				

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