

1 Highlights

2 **Modeling effort in a multispecies recreational fishery; influence of**
3 **species-specific temporal closures, relative abundance, and season-**
4 **ality on monthly angler-trips**

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- 6 • Red snapper and gag temporal management directly influenced recre-
7 ational angler effort along the west coast of Florida
- 8 • The fraction of months open to harvest for both red snapper and gag
9 were both positively associated with effort
- 10 • Red snapper season length was negatively associated with effort, sug-
11 gesting effort concentration
- 12 • Gag grouper season length was not correlated with effort, suggesting
13 effort concentration is not (yet) occurring for this species

14 Modeling effort in a multispecies recreational fishery;
15 influence of species-specific temporal closures, relative
16 abundance, and seasonality on monthly angler-trips

17 A. Challen Hyman^a, David Chagaris^b, Michael Drexler^c, Thomas K. Frazer^a

^a*College of Marine Science, University of South Florida, 140 7th Avenue South, St.
Petersburg, 33701, Florida, USA*

^b*Nature Coast Biological Station, Institute of Food and Agricultural Sciences, University
of Florida, 552 1st St, Cedar Key, 32625, Florida, USA*

^c*The Ocean Conservancy, 600 1st Avenue North, Suite 301, St.
Petersburg, 33701, Florida, USA*

18 **Abstract**

Seasonal harvest restrictions are a common strategy in fisheries management, designed to mitigate fishing pressure on economically and recreationally valuable fish and invertebrate stocks. However, uncertainty regarding recreational fishing effort responses to seasonal closures can lead to unintended consequences for target and non-target species. This is especially true in the Gulf of Mexico reef fishery, where anglers can switch among multiple target species and discard mortality for co-occurring species is high. Therefore, understanding the drivers of recreational fishing effort is needed to support management decisions. This study addresses knowledge gaps by employing a statistical model to analyze the relationships between recreational reef fish effort (measured in angler-trips) and species-specific seasonal management in the Gulf of Mexico along the west coast of Florida. We focused on ecological and management variables surrounding gag (*M. microlepis*), red grouper (*E. morio*), and red snapper (*L. campechanus*), which are among the most recreationally sought-after species targeted along the west coast of Florida. We also considered environmental covariates such as seasonal patterns, inter-annual changes in species abundance, and socioeconomic factors (i.e., numbers of saltwater fishing licenses sold and economic trends). Our analysis indicated considerable variation in effects of seasonal, environmental, and management predictors on recreational effort that were region-specific. Notably, management predictors related to both red snapper and gag, such

as the fraction of a month open to harvest (both species) and the length of the red snapper season, directly influenced recreational effort. Given recent substantial reductions in the Gulf of Mexico gag season, we were particularly interested in the effect of gag management on angler-trips, but we did not find strong evidence that effort concentration has taken place for this species at this time. This information provides foundational insights into the seasonal, biological, and anthropogenic drivers of recreational angler reef fish effort along the west coast of Florida. This model, or related frameworks, could be valuable in forecasting future trends in recreational effort along the west coast of Florida specifically and the Gulf of Mexico more generally, and may be instrumental for managers seeking to comprehend the consequences of changes to seasonal reef fishery management.

19 *Keywords:* Effort concentration, Multispecies management, Gulf of
20 Mexico, Reef fishery

21 **1. Introduction**

22 Effective management is a crucial component of sustainable fisheries.
23 Broadly speaking, fisheries are comprised of commercial and recreational
24 components, which are often regulated using different tactics. Commercial
25 fishing sectors are frequently managed using strict measures such as indi-
26 vidual fishing quotas, limited entry, or vessel monitoring systems (Anderson
27 et al. 2019), which are usually easier to monitor and regulate as landings are
28 often observed directly. In contrast, recreational fisheries present additional
29 management challenges (MacKenzie and Cox 2013; Bohaboy et al. 2022),
30 due in part to substantially larger numbers of individual recreational partici-
31 pants which must be indirectly sampled to monitor catch and effort, as well as
32 heterogeneity in the recreational fleet (e.g., Cox et al. 2002). In these cases,
33 seasonal harvest restrictions are a widely employed fishery management strat-
34 egy to alleviate recreational fishing pressure and achieve sustainable harvest.
35 Seasonal harvest closures are often aligned with spawning seasons to protect
36 or rebuild vulnerable species, and can be extended or shortened based on
37 stock status and catch levels (e.g., National Marine Fisheries Service 2022;
38 Gulf of Mexico Fishery Management Council 2023a,b). However, recreational
39 angler behavioral responses to seasonal closures are complex, poorly under-
40 stood, and often difficult to predict (e.g., Cox et al. 2002; Camp et al. 2016),
41 especially within the context of multispecies fisheries where multiple highly

42 sought-after species co-occur. Consequently, the effectiveness of seasonal
43 management regulations can be compromised or lead to deleterious effects
44 on one or more stocks should anglers respond in unexpected ways (Gentner
45 2004; Beaudreau et al. 2018; Abbott et al. 2018; Trudeau et al. 2022). Under-
46 standing how recreational angler dynamics respond to management changes
47 is therefore crucial for achieving long-term fisheries sustainability (Radom-
48 ski et al. 2001), especially for multispecies fisheries where incidental bycatch
49 cannot be avoided.

50 Various forms of displaced recreational fishing effort can give rise to ad-
51 verse consequences when alterations are made to fishing seasons (Chagaris
52 et al. 2019). Although single species harvest seasons in multispecies fisheries
53 can reduce fishing effort (i.e., the intended effect; Beardmore et al. 2011;
54 Maggs et al. 2012; Trudeau et al. 2022), shorter seasons may not result in
55 reduced catch if anglers intensify their effort on a given species within the
56 shorter fishing window (i.e., effort concentration; Powers and Anson 2016,
57 2018; Farmer et al. 2020). Alternatively, contracted seasons for one species
58 may cause anglers to instead target co-occurring species (i.e., effort redirec-
59 tion; Abbott et al. 2018; Beaudreau et al. 2018). However, effort redirection
60 will not reduce fishing pressure if anglers continue to fish in the same areas
61 for co-occurring, alternative species with open seasons because reductions in
62 fishing effort for the target species may be offset by high discard mortality
63 (Foster et al. 2017; Pulver 2017; Runde et al. 2021; Boyle et al. 2022). Conse-
64 quently, in multispecies fisheries where one or more exploited species coexist,
65 it may be more useful to evaluate how management changes to one or more
66 species within a complex affect fishing effort directed at the entire fishery in
67 aggregate (Chagaris et al. 2019).

68 The Gulf of Mexico (GOM) multispecies reef fishery encompasses a di-
69 verse assemblage of 31 reef-associated finfish species, primarily managed with
70 seasonal restrictions (i.e., opening and closing dates), size limits, and catch
71 quotas that are species-specific. Commercial, for-hire, and recreational data
72 suggest this multispecies fishery is well mixed. Catch compositions of mul-
73 tiple species within the fishery tightly overlap, particularly notable among
74 species within respective shallow-water, mid-water, and deep-water snapper
75 and grouper complexes (Farmer et al. 2016). However, the degree of coupling
76 between specific species is dependent on the sector, gear, and region (Farmer
77 et al. 2016). Presently, two species – greater amberjack, *Seriola dumerili* and
78 gag, *Mycteroperca microlepis* (SEDAR70 2020; SEDAR72 2021) – are rec-
79 ognized as overfished (i.e., spawning stock biomass is too low), while other

80 species, including red grouper *Epinephelus morio*, have experienced recent
81 population declines (SEDAR61 2018; SEFSC 2022). Depletion of multiple
82 stocks and the limited recovery of others (e.g., greater amberjack; SEDAR70
83 2020) indicate that the restrictive regulations placed on these species have
84 not reduced fishing mortality as expected, suggesting that a more nuanced
85 management approach is required for this multispecies fishery (Chagaris et
86 al. 2019). In particular, fishing mortality rates in the recreational sector have
87 remained high, and the magnitude of regulatory discards can exceed directed
88 harvest (Tetzlaff et al. 2013).

89 Alternative approaches such as total seasonal effort restrictions (i.e., no
90 fishing of any reef fish species) have been explored for this multispecies fish-
91 ery, but the performance of different management scenarios was sensitive to
92 assumptions about how effort would redistribute throughout the year (Cha-
93 garis et al. 2019), which has not been estimable. In addition, practical con-
94 straints make such total closures unlikely, as maximizing access (fishing days)
95 across all species is a desired stakeholder and management goal. This un-
96 derscores the need to improve our understanding of recreational responses
97 to species-specific closures in multispecies fisheries. Statistical modeling of
98 recreational angler effort may improve understanding of angler behavior and
99 provide valuable insights which could improve outcomes to stock status (e.g.,
100 Farmer et al. 2020; Trudeau et al. 2022).

101 This study develops a statistical model to dissect the relationships be-
102 tween recreational fishing effort (measured in angler-trips) and species-specific
103 seasonal management in the GOM along the west coast of Florida. We
104 focused on ecological and management variables surrounding gag (*M. mi-*
105 *crolepis*), red grouper (*E. morio*), and red snapper (*Lutjanus campechanus*),
106 which are the three most sought-after species recreationally in the west coast
107 of Florida. Our central objectives were to identify and quantify the main
108 drivers of regional effort along the west coast of Florida. Moreover, the
109 declining stock size of one species – gag – led to major reductions in the
110 most recent recreational harvest season (Gulf of Mexico Fishery Manage-
111 ment Council 2023b), leading to concerns that such substantial reductions
112 in season length might result in effort concentration for this species. Hence,
113 we were especially interested in the effects of seasonal management for each
114 species considered, where feasible, to understand how recreational reef fish
115 effort responded to changes in these variables. In addition, we included en-
116 vironmental covariates such as seasonality and species-specific abundance as
117 well as social and economic factors such as the number of saltwater fishing li-

118 cense sales, median household income, and fuel costs. Through this research,
119 we aim to inform more effective management strategies within multispecies
120 recreational fisheries.

121 **2. Material and Methods**

122 *2.1. Survey data*

123 We estimated monthly angler-trips (our proxy for angler effort) using
124 [survey data](#) from the National Marine Fisheries Service (NMFS) Marine
125 Recreational Information Program (MRIP). A main component of MRIP
126 is the [Access Point Angler Intercept Survey \(APAIS\)](#), which is used to col-
127 lect catch-per-trip data from anglers fishing from shore, private boats, and
128 for-hire vessels based on in-person dockside interviews of anglers recently re-
129 turning from a fishing trip. APAIS also collects information on location, dis-
130 tance from shore, primary and secondary target species, and other pertinent
131 information as predictors modeling angler behavior. Dockside intercepts are
132 weighted to extrapolate interviews to the population level using the [Fishing](#)
133 [Effort Survey \(FES\)](#). Individual sample weights can be understood as the
134 number of additional interviews that will be represented by the interview
135 that was sampled (NMFS OST 2023). This weight is multiplied by the inter-
136 view data collected through a particular questionnaire to determine weighted
137 values (see [MRIP estimation methods](#) for more information). MRIP survey
138 data prior to 2004 were not compatible with complex survey extrapolation
139 techniques. As a result, we limited our focus to data from 2004 to 2023 (see
140 [the MRIP Recreational Fishing Data Downloads Guide](#) for details). We also
141 limited our consideration to APAIS interviews where anglers either declared
142 at least one of the 31 reef species as a primary or secondary target or caught
143 (retained or discarded) one of the 31 species. Finally, we only considered
144 nearshore and offshore trips (i.e., no shoreline or beach trips), so that infer-
145 ences were constrained to the reef fishery. As a result, only private vessel and
146 charter trips were considered (accounting for 80% and 20% of all angler-trips
147 considered, respectively, Fig. S1a). Monthly average angler-trips (scaled by
148 mode) for each region suggested patterns among modes were similar (Fig.
149 S1b). For all MRIP estimation procedures, we employed modified [custom](#)
150 [domain analyses templates](#) using the the R language for statistical comput-
151 ing (R Core Team 2023) to aggregate FES-weighted angler-trips at varying
152 temporal and spatial domains. To derive angler-trip estimates (effort), we
153 took the product of the total number of anglers in a party and the sample

154 weight for each APAIS entry. For reproducibility, all modified templates and
155 related estimation files are located in an [online repository](#).

156 *2.2. Species considered*

157 To identify the most frequently targeted recreational species within the
158 GOM reef fishery, we estimated the total number of directed angler-trips
159 for each of the 31 species from 2004 to 2023. Here, our spatial domain was
160 the entire west coast of Florida (sub region 7 [Gulf of Mexico] and state 12
161 [Florida FPS code]), while our temporal domain was annual. To calculate
162 annual estimates of angler-trips for each species, we multiplied each individ-
163 ual entry by the MRIP survey weights and summed each metric over each
164 year (NMFS OST 2023), using the MRIP template mentioned above. The
165 three most popular reef fish species were red snapper, gag, and red grouper
166 (Fig. S2). Hence, we limited our focus to these species.

167 *2.3. Data aggregation*

168 For our modeling framework, we considered monthly angler-trips from
169 two Florida sub-state regions along the GOM as our response variable. Here,
170 we defined our spatial domain as [MRIP Florida charter mode regions 1 and](#)
171 [2](#) (stratification variable FL_REG; herein denoted “Panhandle” and “Penin-
172 sula”, respectively; Fig. 1), while our temporal window was month. Since
173 we considered recreational effort from both private and charter modes in
174 our study, we elected to use the Florida charter mode regions as our spatial
175 strata because these regions were more spatially coarse than Florida regions
176 used to assess private mode fishing, although an earlier three-region model
177 yielded comparable results. In each Florida charter region (herein, denoted
178 “Region” for simplicity) and month, FES-weighted APAIS information was
179 aggregated to generate consolidated, region-specific monthly estimates. For
180 angler-trips in each region-month-year t , we summed the product of the num-
181 ber of individuals in the party by the FES weight for all I interviews in that
182 spatiotemporal domain.

$$F_t = \sum_{i=1}^I \text{Party}_{t,i} \cdot W_{t,i}$$

183 This aggregation resulted in a time-series comprising 240 monthly esti-
184 mates (12 months x 20 years) in each region, although there were five missing

185 values (December in years 2006, 2014, 2018, 2019, and 2020) in the Panhan-
186 dle (235 estimates), amounting to a total of 475 estimates across both re-
187 gions. Notably, although this aggregation procedure is consistent with formal
188 MRIP templates designed to estimate mean fishing effort, it ignores observa-
189 tion uncertainty associated with incomplete sampling of the population (i.e.,
190 sampling error). Therefore we stress that some caution is warranted when
191 interpreting the results of these analyses due to the underlying imprecision
192 of our response variable.

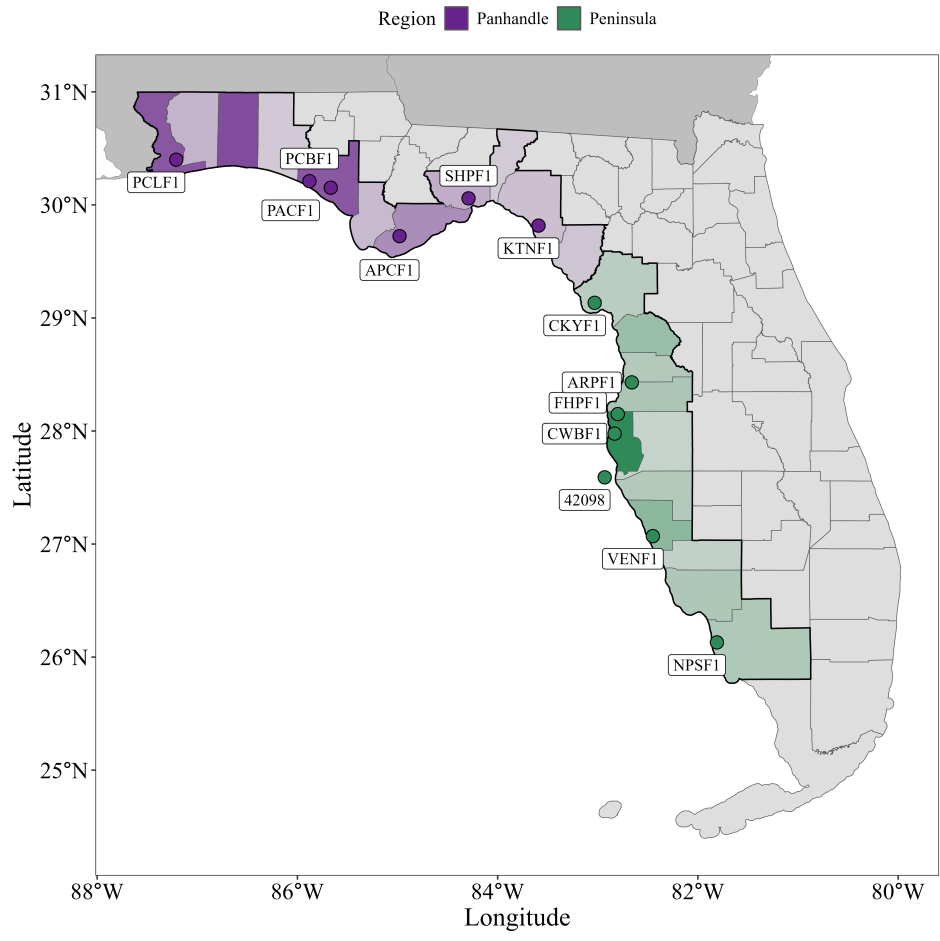


Figure 1: Map of Florida counties and NOAA Buoy locations used to estimate mean wind speed with corresponding buoy labels. Counties and buoys considered in our study are colored by MRIP Florida regions 1 (Panhandle) and 2 (Peninsula), while counties not considered are colored grey. More vivid coloration corresponds with higher relative recreational effort (angler-trips), whereas weaker coloration corresponds with lower recreational effort

193 *2.4. Predictors*

194 A combination of social, economic, environmental, and management vari-
 195 ables (herein, predictors) were initially considered as potential determinants
 196 of recreational effort among regions. The following is a brief description of
 197 each predictor, the rationale for its consideration, and how the data were
 198 collected. Additional details on associated predictor symbology are in Table

199 1. Information on relevant predictors was obtained from state and federally
 200 published data sources.

Table 1: Symbology, and descriptions of each variable considered.

Variable	Description
PH	Regional effect of the Panhandle
PN	Regional effect of the Peninsula
$CPUE_{Gag}$	Monthly gag region-specific mean recreational CPUE (catch per angler) from prior year when harvest season is open
$CPUE_{RG}$	Monthly red grouper region-specific mean recreational CPUE (catch per angler) from prior year when harvest season is open
$CPUE_{RS}$	Monthly red snapper region-specific mean recreational CPUE (catch per angler) from prior year when harvest season is open
$Open_{Gag}$	Fraction of a month open to gag harvest
$Open_{RS}$	Fraction of a month open to red snapper harvest
$Season_{Gag}$	Log-length of the gag season when harvest season is open
$Season_{RS}$	Log-length of the red snapper season when harvest season is open
Sales	Number of recreational 12-month saltwater angler licenses sold in Florida from the previous year (millions)
Ratio	Ratio of Florida real median household income (adjusted for inflation using 2023 dollars) to Florida mean gasoline price
Wind	Region-specific average wind speed (m/s)
sin_{12}	Annual (12-month) sinusoidal term
cos_{12}	Annual (12-month) cosinusoidal term
sin_6	Semi-annual (6-month) sinusoidal term
cos_6	Semi-annual (6-month) cosinusoidal term

201 2.4.1. CPUE

202 Availability of harvestable fish is one fundamental driver of fishing ef-
 203 fort. Higher availability of fish is positively linked to angler satisfaction due
 204 to higher associated catch-per-unit-effort (CPUE) (Arlinghaus and Mehner
 205 2005; Arlinghaus 2006). Offshore fishing is a resource-intensive exercise re-

206 quiring time, fuel, and other indirect costs. If the expected CPUE is too low,
 207 the benefits of embarking on a recreational fishing trip may not outweigh the
 208 costs, and, as a result, fewer anglers may elect to fish (Cox et al. 2002; Post
 209 et al. 2003). Hence, we expected a generally positive relationship between
 210 CPUE and effort. Moreover, since anglers would conceivably base the deci-
 211 sion to fish on past conditions, we expected effort would be related to CPUE
 212 in the previous year. For each region-month-year considered, we estimated
 213 CPUE for each species as the weighted average of all I CPUE estimates (de-
 214 fined as total fish caught divided by number of individuals in party from a
 215 given interview i) within that spatiotemporal unit:

$$\text{CPUE}_{s,t} = \frac{\sum_{i=1}^I W_{t,i} \cdot \frac{C_{s,t,i}}{\text{Party}_{t,i}}}{\sum_{i=1}^I W_{i,t}}$$

216 where $C_{s,t,i}$ is the total catch (harvested and discarded) of species s in region-
 217 month-year t and interview i . Monthly CPUE estimates for each year be-
 218 tween 2003-2022 were used as a lagged CPUE for each species for corre-
 219 sponding months in the years 2004-2023. We chose a monthly resolution to
 220 ensure that this variable reflected both inter-annual patterns of abundance
 221 and intra-annual patterns in catchability (i.e., overall high abundance is less
 222 likely to matter at times of year when catchability is low). Moreover, we
 223 expected that CPUE of a given species would only influence trips when the
 224 season for that species was open. Lagged CPUE estimates were therefore
 225 multiplied by the fraction of each month open to harvest (see Section 2.4.2
 226 immediately below). When the season was closed, CPUE did not impact
 227 angler-trips.

228 2.4.2. Management

229 A common assumption in recreational fisheries management is that re-
 230 ductions in fishing season lengths result in decreased effort by reducing the
 231 number of opportunities to fish. To account for this, we included the frac-
 232 tion of a month open to fishing for a given species in each year within the
 233 time series. We expected that months with fewer days open (i.e., smaller
 234 fractions) would result in lower monthly angler-trips. On the other hand,
 235 evidence suggests that anglers may also compensate for shorter fishing sea-
 236 sons by embarking on more fishing trips when the season is open, resulting
 237 in effort concentration, particularly for highly sought-after species (Powers

238 and Anson 2016, 2018; Trudeau et al. 2022). Therefore, we also included
239 the length of each recreational fishing season as a predictor. We hypothe-
240 sized that shorter fishing seasons would result in higher effort in a given open
241 month relative to longer seasons (i.e., a negative effect).

242 Recreational species-specific seasonal opening and closure data for gag,
243 red grouper, and red snapper were obtained from Florida Fish and Wildlife
244 Conservation Commission (Fig. 2), which was used to construct seasonal
245 opening/closure datasets at the daily resolution for each species. These data
246 were subsequently aggregated to the month level to remain consistent with
247 the APAIS trip information. For each species and each year, we first obtained
248 all dates when a given season was open. We subsequently counted the number
249 of days open (1) for the entire season and (2) for each month. Here, we
250 considered the natural log of season length, instead of the raw value (number
251 of days open in each year), to test the assumption that anglers are more
252 responsive to changes in season length when the season is already very short
253 than to changes in season length when the season is longer. During longer
254 seasons, the number of days open to fish may exceed the number of trips
255 an angler would like to take during a year. However, as the season narrows,
256 the total number of days open to fish may become increasingly constrained,
257 causing anglers to increasingly alter their behavior to take more trips during
258 months when the season remains open. Moreover, effort concentration for any
259 given species would only manifest in months that were open to fishing. For
260 each species, we multiplied the log-season length for each year by the fraction
261 of each month open. Similar to relative abundance, if a fishing season was
262 closed in a given month, the effect of log-season length was simply zero. For
263 simplicity, herein we refer to this variable as “season length”. Finally, only
264 8.7% of days considered between 2004 to 2023 were closed to red grouper
265 recreational harvest in both state and federal waters (Fig. 2). Consequently,
266 we did not include red grouper management terms in this model due to lack
267 of contrast.

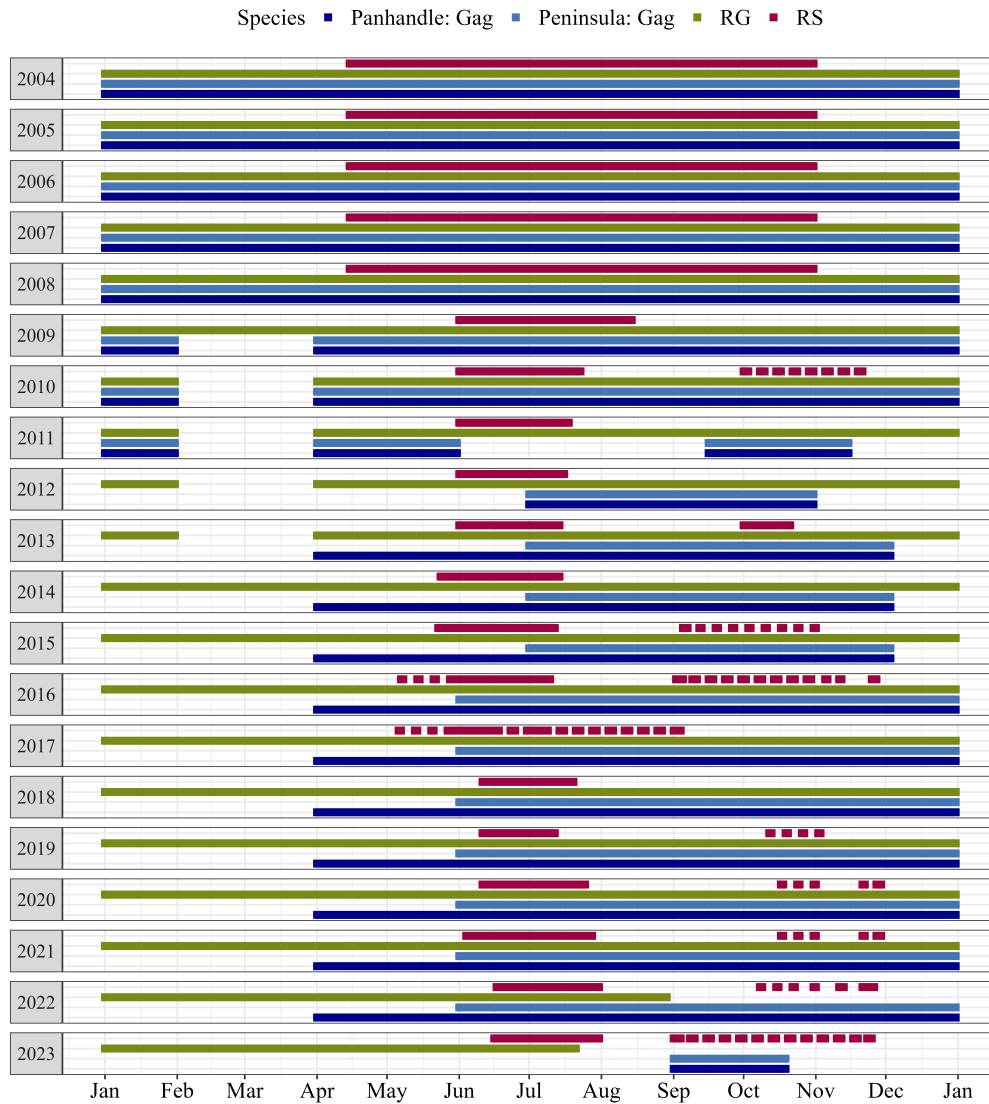


Figure 2: Time-series of recreational seasons (state and federal waters) for gag, red grouper, and red snapper among years studied. Between 2013 and 2022, gag was open to harvest in Franklin, Wakulla, Jefferson, and Taylor counties (Panhandle) from April 1st to June 30th in addition to the regular gag season between 2013 and 2022. Consequently, gag seasons vary by region for these years. Breaks in the red snapper seasons reflect weekend openings (Fri-Sun). Gag = gag; RG = red grouper; RS = red snapper.

268 *2.4.3. Socioeconomic variables*

269 In addition to environmental and management variables, variation in an-
270 thropogenic factors may also influence patterns in angler trips. Specifically,
271 we expected the total number of saltwater anglers to positively influence the
272 number of fishing trips taken in a given month. We assumed that annual
273 12-month Florida saltwater fishing license sales would be proportional to the
274 saltwater angler population and used this variable as a proxy for angler abun-
275 dance Florida saltwater license sales were obtained from the [Gulf States Ma-
276 rine Fisheries Commission](#) [?]. Moreover, as trips to and from offshore reefs
277 require considerable travel costs, we expected the price of fuel to be nega-
278 tively associated with monthly effort (Chan et al. 2017; Pascoe et al. 2020;
279 Farmer et al. 2020), and income to be positively associated with monthly
280 effort. Importantly, income relative to fuel prices represents a reasonable
281 proxy for financial resources available for discretionary spending, which we
282 hypothesized would be an important economic influence on fishing effort.
283 Therefore, we also included the ratio of Florida median income to fuel prices
284 – both of which were adjusted for inflation *a priori* using the consumer price
285 index (CPI; using 2023 dollars). Fuel price and CPI data were obtained from
286 the U.S. Energy Information Administration 2023, and the U.S. Bureau
287 of Labor Statistics 2023, respectively. Median Florida income was obtained
288 through the U.S. Census Bureau 2022.

289 *2.4.4. Weather*

290 The decision to embark on a fishing trip is often dependent on weather
291 conditions. Seasonal weather along Florida’s west coast is generally more
292 favorable to fishing in summer and early fall. On a monthly scale, we hy-
293 pothesized that recreational anglers would be less likely to fish if offshore
294 wind conditions sufficiently high to the point of being hazardous. We in-
295 cluded the mean wind speed (m/s) in each month as a predictor. Here, we
296 obtained wind speed data from the NOAA National Data Buoy Center from
297 13 coastal buoys along the Florida Panhandle and western peninsular coast-
298 line (Fig. 1; U.S. Department of Commerce 2022, 2023j,i,h,b,k,g,d,c,f,e,a,l).
299 These buoys were chosen for their location and associated data. Daily mean
300 wind speeds were estimated from all buoys which had data available for a
301 given day, which was subsequently averaged to obtain monthly average wind
302 speed estimates for each region. This is in contrast to Farmer et al. (2020),
303 which estimated the fraction of fishable days using both mean wind speeds
304 and mean wave height. Unfortunately, wave height data for buoys considered

305 in this study were only available after 2010, and only for select buoys in each
306 region. Hence, we limited our consideration to wind speed, which tends to
307 be correlated with wave height.

308 *2.4.5. Seasonality*

309 Harmonic regression terms were included as predictors to account for
310 seasonal variation in angler behavior. Many species exhibit marked seasonal
311 patterns in distribution and behavior. For example, many grouper species
312 form seasonal spawning aggregations or otherwise exhibit seasonal movement
313 related to spawning behavior (Koenig et al. 1996; Coleman et al. 2011; Grüss
314 et al. 2017). Meanwhile, red snapper exhibit strong site fidelity to structured
315 habitats, such as natural and artificial reefs (Topping and Szedlmayer 2011a),
316 although movement in response to seasonal changes in environmental condi-
317 tions are frequently reported (Topping and Szedlmayer 2011b; Switzer et
318 al. 2015) and red snapper also tend to be more active in warmer months
319 (Piraino and Szedlmayer 2014). Seasonal movement and aggregation behav-
320 ior directly affects the vulnerability of these species to fishing pressure (e.g.,
321 Biggs et al. 2021) and may also influence intra-annual angler motivation to
322 target a given species. To account for this, we included sinusoidal and cosinu-
323 soidal harmonic terms operating under two periods (annual and semi-annual)
324 to account for the aforementioned seasonal patterns in distribution and avail-
325 ability (e.g., for the annual sinusoidal term, $\sin_{12,m} = \sin(\frac{2\pi \cdot m}{12})$ where m is
326 a given month).

327 *2.5. Analysis*

328 We employed a gamma distribution to characterize the general reef fish
329 effort in our modeling framework. Monthly angler-trip estimates, being posi-
330 tive with a lower bound of zero, exhibited a pronounced positive skewness.
331 These distinctive characteristics rendered the gamma distribution an appro-
332 priate fitting choice for effectively describing this response variable. The
333 complete effort model is therefore expressed as:

$$\begin{aligned}
F_t &\sim \text{Gamma}(\alpha_t, \sigma_t) & (1) \\
\alpha_t &= \frac{\sigma_t}{\mu_t} \\
\mu_t &= \exp\left(\beta_0 + \sum_{p=1}^P x_{t,p}\beta_p\right) \\
\sigma_t &= \exp\left(\rho_0 + \sum_{q=1}^Q z_{t,q}\rho_q\right) \\
\beta, \rho &\sim N(0, 10)
\end{aligned}$$

334 where F_t denotes the number of angler-trips estimated in region-month-year
335 t . Meanwhile, $\text{Gamma}(y|\alpha, \sigma)$ is the Gamma probability density function
336 such that:

$$\text{Gamma}(y|\alpha, \sigma) = \frac{\alpha^\sigma}{\Gamma(\sigma)} y^{\sigma-1} \exp(-\alpha y), \quad y \geq 0$$

337 where α denotes the inverse-scale parameter, and σ denotes the shape pa-
338 rameter, and $\Gamma(\cdot)$ denotes the Gamma function. The mean of the Gamma
339 distribution, μ , can be expressed as $\mu = \frac{\sigma}{\alpha}$. The ln mean μ_t is linearly related
340 to an intercept (β_0) and set of P linear predictors ($x_{t,1}, \dots, x_{t,P}$) and corre-
341 sponding coefficients (β_1, \dots, β_P). Here, the shape parameter σ_t is explicitly
342 modeled based on intercept ρ_0 and linear predictors ($z_{t,1}, \dots, z_{t,Q}$) based on
343 our two regions and corresponding coefficients ρ_1, \dots, ρ_Q through a log-link
344 function. These specifications relaxed the assumptions on variance in our
345 modeling framework. The complete set of predictors and specific model co-
346 efficients are located in Tables S1 and S2. For model coefficients for both
347 the mean structure (β) and error term (ρ), we supplied weakly informative
348 priors with mean 0 and variance 100 to facilitate with model convergence.

349 2.5.1. Model implementation

350 All data analyses, transformations, and visualizations were carried out
351 using the R programming language for statistical computing (R Core Team
352 2023) and the Stan probabilistic programming language for Bayesian sta-
353 tistical modeling (Gelman et al. 2015; Carpenter et al. 2017; Stan Devel-
354 opment Team 2022) through the `brms` package (Bürkner 2017), leveraging

355 Hamiltonian Monte Carlo (HMC) sampling from the joint posterior. We
356 ran four parallel Markov chains, each undergoing 1,000 iterations for the
357 warm-up/adaptive phase and an additional 1,000 iterations to obtain pos-
358 terior samples, resulting in a total of 4,000 draws for posterior inference.
359 In terms of scientific relevance (i.e., significance), we focused on covariates
360 and interactions whose posterior distributions excluded 0 within their 80%
361 highest density probability interval (McElreath 2018), following the rationale
362 provided in Hyman et al. 2022.

363 2.5.2. Temporal autocorrelation

364 In time series models, the temporal structure of the data often requires
365 consideration because sequential estimates often do not represent indepen-
366 dent replicates, as the presence of latent variables may introduce temporal
367 autocorrelation. We initially considered a model with a similar structure
368 that also included an AR(1) term. However, in- and out-of-sample fit were
369 comparable among models with and without the AR(1) term, and partial au-
370 tocorrelation plots did not indicate strong temporal autocorrelation among
371 the residuals of the simpler model (Fig. S3c). Most notably, partial autocor-
372 relation plots indicated that the inclusion of an AR(1) term did not appre-
373 ciably reduce temporal autocorrelation (not shown). As a consequence, we
374 considered the simpler model to be more appropriate under the principle of
375 parsimony.

376 2.6. Marginal effects

377 We estimated marginal effects to evaluate the association between monthly
378 angler-trips in each region and meaningful predictors while accounting for re-
379 gional categorical effects. Opting for flexibility, we allowed the coefficients of
380 all continuous predictors to vary across both MRIP regions. Consequently,
381 the raw coefficient estimates for the Peninsula were determined in relation
382 to the corresponding estimates for the Panhandle (our reference level). In
383 other words, coefficients for the Peninsula are linear contrasts to the coef-
384 ficient estimates for the Panhandle. Rather than presenting the Peninsula
385 contrasts, we opted to directly report the region-specific intercept and con-
386 tinuous predictor coefficients. We summed correlated posterior draws from
387 the reference coefficient of the Panhandle to the corresponding coefficients
388 of the Peninsula. For instance, the effect of gag CPUE in the Peninsula was
389 computed as the sum of the effect from the Panhandle and the effect from the
390 Peninsula relative to the Panhandle ($\beta_{PN:CPUE_{Gag}} = \beta_2 + \beta_3$; Table S1), while

391 the marginal effect of gag CPUE in the Panhandle ($\beta_{PH:CPUE_{Gag}}$) is simply
 392 β_2 . The marginal posterior distribution summary statistics utilize posterior
 393 median values and 80% confidence intervals.

394 2.7. Conditional effects

395 To conceptualize effort concentration with respect to progressively nar-
 396 rower fishing seasons, we developed conditional effects plots to depict the
 397 expected change in angler-trips in each region under a range of red snapper
 398 management conditions. Notable effort concentration was only apparent in
 399 red snapper management, and as a result we only focused on this species.
 400 First, we fixed all non-management covariates to conditional values. For each
 401 region, we conditioned Florida median income to fuel, and saltwater fishing
 402 license sales on monthly 2023 values, while conditional species-specific CPUE
 403 and wind speed was fixed at the region-specific, monthly averages among all
 404 years. Harmonic terms did not vary inter-annually and were simply fixed
 405 at their respective monthly values. To limit inference to a single month, we
 406 arbitrarily fixed the temporal window to the month of June. Next, we esti-
 407 mated the posterior predictive distribution of angler trips under total season
 408 lengths for red snapper ranging from 40 to 200 days (the minimum and maxi-
 409 mum season length observed for red snapper, respectively) and fraction of the
 410 month open to harvest set at 0, 0.5, and 1. To isolate effects of management,
 411 we fixed the management values of all other species at zero. We subsequently
 412 calculated our season length variable as the log number of days open multi-
 413 plied by the fraction of the month open to harvest (Section 2.4.2). Finally,
 414 we estimated the conditional posterior predictive distribution of angler-trips
 415 for each management combination (fraction of month open to harvest and
 416 season length variables) in each region. Conditional posterior predictive dis-
 417 tributions of angler-trips here refer to the conditional expectation, μ_{cond} , as
 418 a function of the entire joint posterior distribution of coefficients β and a
 419 matrix of conditional predictors X_{cond} . Each conditional posterior predictive
 420 draw d of the mean value $\mu_{cond}^{(d)}$ was estimated using the following equation:

$$\mu_{cond}^{(d)} = \exp\left(\beta_0^{(d)} + \sum_{p=1}^P x_{cond,p} \beta_p^{(d)}\right) \quad (2)$$

421 where $\beta_p^{(d)}$ denotes the d^{th} draw from the posterior predictive distribution of
 422 the p^{th} predictor coefficient.

423 *2.8. Out of sample predictions*

424 A major objective of fisheries management is to forecast how changes in
425 management will impact future reef fish effort. To this end, we randomly
426 withheld the 50 monthly effort estimates (in total) across both regions and
427 subsequently generated posterior predictive distributions for out-of-sample
428 observations as a prediction exercise. Both in-sample and out-of-sample pre-
429 dictive performance were used in model validation.

430 **3. Results**

431 *3.1. Model diagnostics*

432 Time-series of observed versus predicted plots, diagnostic plots, and cross
433 validation indicated that our statistical model was robust. Monthly angler-
434 trip estimates for each region and uncertainty conformed with in-sample esti-
435 mates of monthly angler-trips for both regions (Fig. 3). Moreover, diagnostic
436 scatter-plots of median predicted versus observed reef fish effort suggested ad-
437 equate model fit (Figs. S3a and S3b). Importantly, 87% and 82% of observed
438 data withheld for out-of-sample cross validation fell within the nominal 80%
439 posterior predictive intervals for the Panhandle and Peninsula, respectively
440 (85% overall), suggesting that this model was also useful in forecasting future
441 trends in recreational effort along the west coast of Florida.

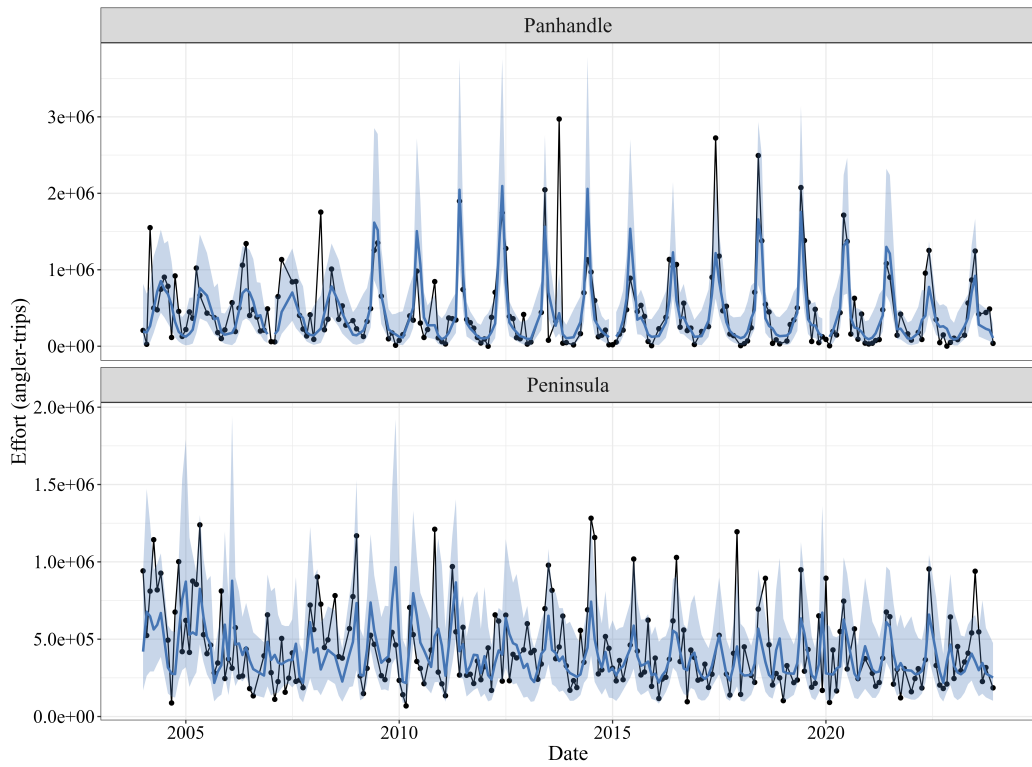


Figure 3: Observed (black) and expected (blue) monthly reef angler-trips for the Panhandle (top panel) and Peninsula (bottom panel) between 2004 and 2023. Bands denote upper and lower 80% posterior predictive intervals. Points shaded black denote observations.

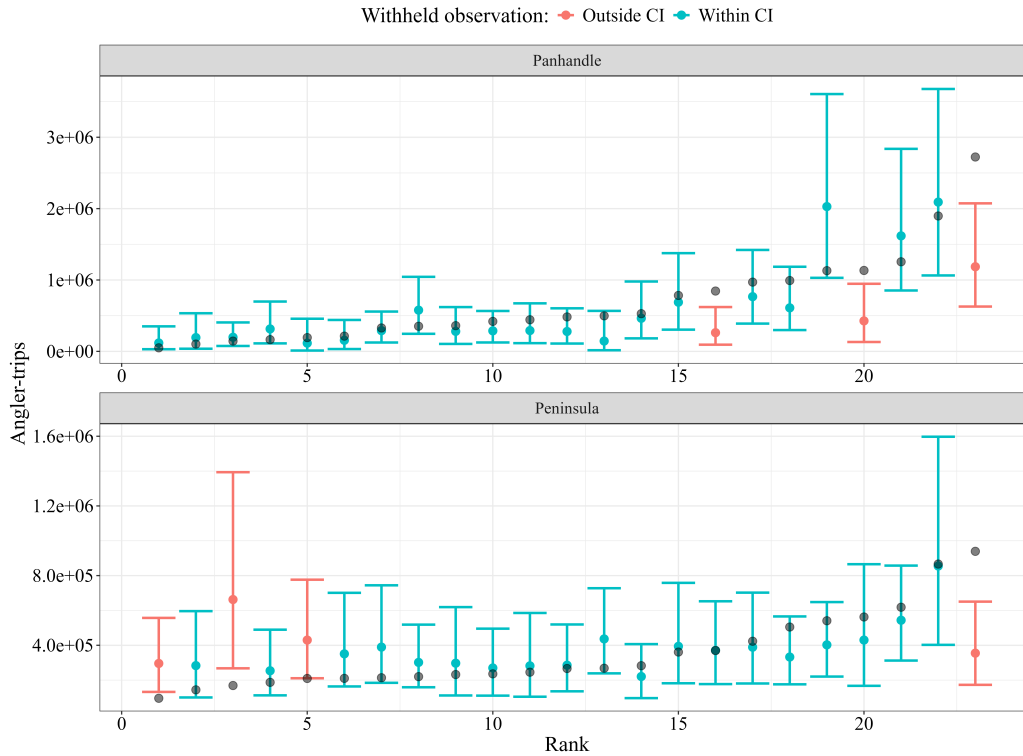


Figure 4: Out-of-sample cross validation results for withheld monthly angler-trips, Panhandle (top row), and Peninsula (bottom row) between 2004 and 2023. Grey points denote withheld monthly angler-trip estimates, while colored points and error bars denote median and nominal 80% Bayesian prediction intervals derived from posterior predictive distributions. Red bars indicate an observed value is outside the prediction interval, while blue bars indicate an observed value is within the prediction interval. For each region, estimates are presented in order of increasing total value (denoted “Rank”).

442 3.2. Panhandle

443 In the Panhandle, nine of 20 predictors significantly explained variation
 444 in monthly angler-trips (Table 2). The fraction of the month open to red
 445 snapper harvest positively associated with monthly angler-trips, while red
 446 snapper season length was negatively associated with monthly angler-trips.
 447 Both the annual harmonic terms also explained variation in monthly angler-
 448 trips in the Panhandle. Finally, the annual sinusoidal and semi-annual
 449 sinusoidal harmonic terms meaningfully impacted the shape parameter in
 450 the Panhandle.

Table 2: Posterior summary statistics (median and 80% CIs) for region-specific slope and intercept coefficients for μ (β) and σ (ρ). Region-specific, marginal coefficient estimates are calculated using methodology outlined in Section 2.6. Coefficient terms with asterisks denote posterior distributions of parameters that excluded 0 within their 80% CI. For plots depicting distributions of standardized regression coefficients, see Fig. S4.

Predictor	Panhandle			Predictor	Peninsula		
	10%	50%	90%		10%	50%	90%
β_{PH}^*	12.042	13.078	14.137	β_{PN}^*	11.494	12.318	13.192
$\beta_{CPUE_{Gag}}$	-0.052	0.131	0.324	$\beta_{PN:CPUE_{Gag}}^*$	0.362	0.554	0.756
$\beta_{CPUE_{RG}}$	-0.46	0.459	1.415	$\beta_{PN:CPUE_{RG}}^*$	0.059	0.162	0.263
$\beta_{CPUE_{RS}}$	-0.134	0.389	0.926	$\beta_{PN:CPUE_{RS}}$	-0.994	0.43	2.043
$\beta_{Open_{Gag}}$	-2.102	-0.518	0.98	$\beta_{PN:Open_{Gag}}^*$	0.25	1.535	2.985
$\beta_{Open_{RS}}^*$	3.741	4.802	5.885	$\beta_{PN:Open_{RS}}$	-0.88	0.103	1.087
$\beta_{Season_{Gag}}$	-0.17	0.103	0.393	$\beta_{PN:Season_{Gag}}$	-0.5	-0.24	0.012
$\beta_{Season_{RS}}^*$	-1.158	-0.917	-0.7	$\beta_{PN:Season_{RS}}$	-0.246	-0.056	0.146
β_{Sales}	-3.616	-1.499	0.54	$\beta_{PN:Sales}$	-0.123	1.701	3.321
β_{Ratio}	-0.04	0.088	0.212	$\beta_{PN:Ratio}$	-0.119	-0.039	0.048
β_{Wind}	-0.169	-0.037	0.1	$\beta_{PN:Wind}$	-0.154	-0.076	0.005
$\beta_{sin_{12}}^*$	0.178	0.286	0.38	$\beta_{PN:sin_{12}}^*$	0.152	0.23	0.304
$\beta_{cos_{12}}^*$	-0.673	-0.517	-0.362	$\beta_{PN:cos_{12}}$	-0.142	-0.037	0.073
β_{sin_6}	-0.114	-0.019	0.081	$\beta_{PN:sin_6}^*$	-0.176	-0.107	-0.036
β_{cos_6}	-0.148	-0.026	0.089	$\beta_{PN:cos_6}^*$	0.115	0.192	0.263
ρ_{PH}^*	0.709	0.84	0.96	ρ_{PN}^*	1.289	1.423	1.543
$\rho_{sin_{12}}$	-0.247	-0.078	0.11	$\rho_{PN:sin_{12}}^*$	0.006	0.178	0.357
$\rho_{cos_{12}}^*$	-1.005	-0.799	-0.598	$\rho_{PN:cos_{12}}^*$	-0.542	-0.347	-0.165
$\rho_{sin_6}^*$	-0.456	-0.248	-0.053	$\rho_{PN:sin_6}^*$	-0.381	-0.208	-0.028
ρ_{cos_6}	-0.314	-0.117	0.072	$\rho_{PN:cos_6}$	-0.277	-0.088	0.128

451 3.3. Peninsula

452 In the Peninsula, lagged gag and red grouper CPUE as well as the fraction
453 of a month open to gag were all positively associated with monthly angler-
454 trips (Table 2). Seasonally, the annual sinusoidal term and both semi-annual
455 harmonic terms meaningfully explained variation in monthly angler-trips in
456 the Peninsula. Meanwhile, both annual harmonic terms and the semi-annual
457 sinusoidal term influenced the shape parameter in the Peninsula.

458 *3.4. Conditional effects*

459 Expected angler-trips conditioned on predictor values outlined in Section
460 [2.7](#), demonstrated the importance of red snapper management on angler
461 trips in the Panhandle (Fig. [5](#)). Under any given season length, expected
462 effort was highest when the month was completely open to harvest and lowest
463 when the month was completely closed (Open_{RS} set to 1 and 0, respectively).
464 However, differences in the conditional expectation among the fractions of the
465 month open were considerably larger when the season was very short, whereas
466 80% CIs increasingly overlapped (suggesting statistical equivalence) under
467 scenarios with progressively longer seasons. In contrast to the Panhandle,
468 neither the fraction of the month open to red snapper nor red snapper season
469 length had any effect on expected angler-trips (Table [2](#)).

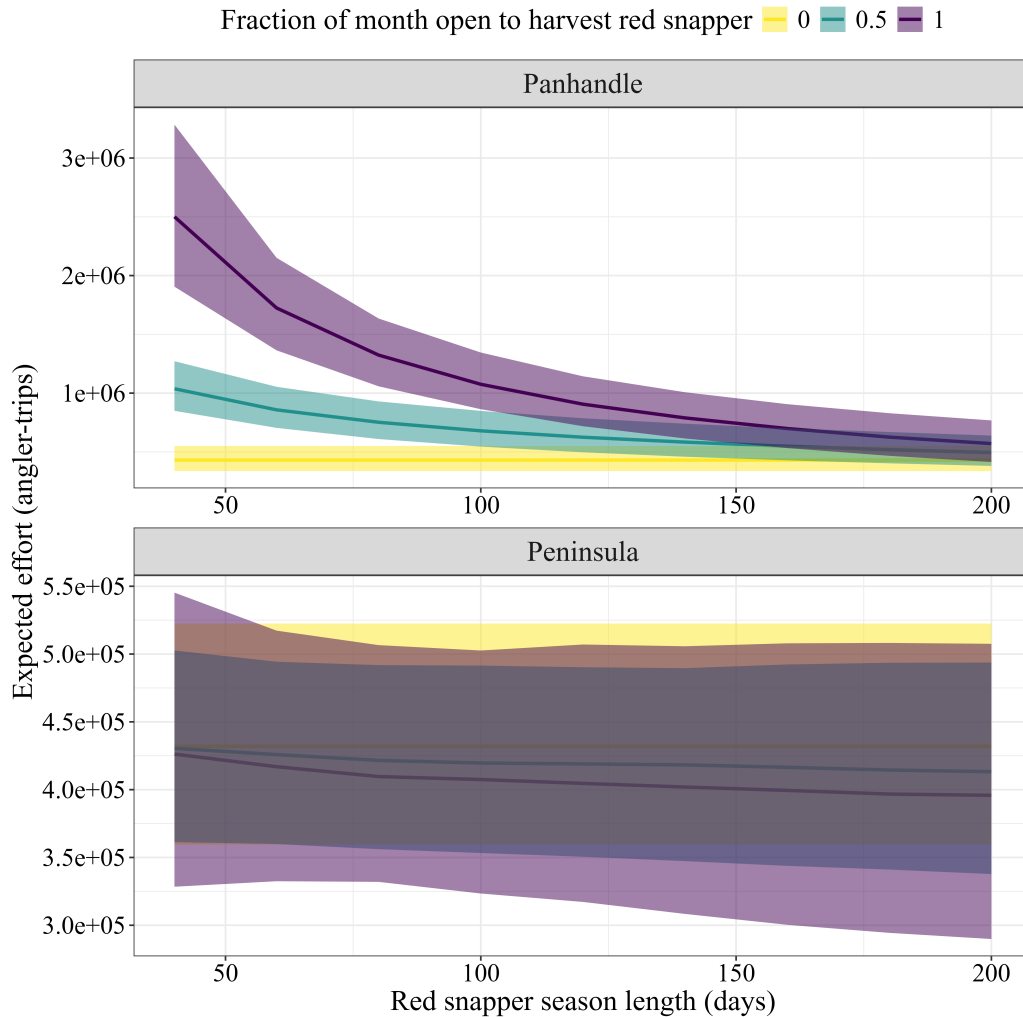


Figure 5: Conditional effects plots depicting the conditional expectation (μ_{cond}) of angler-trips under an array of red snapper management conditions in the Panhandle (top row), and Peninsula (bottom row). Colored lines and bands denote median and nominal 80% Bayesian conditional prediction intervals derived from posterior predictive distributions using the approach outlined in Section 2.7. Values are shaded based on the fraction of a month open to red snapper harvest.

470 3.5. Comparisons among regions

471 Comparisons between regions revealed several statistically distinct spatial
 472 differences in the mean structure of the model (Tables 2, S1, and S2). Specif-

473 ically, in the Panhandle, the red snapper management terms exerted a much
474 stronger influence on angler-trips than in the Peninsula (Fig. 5). Meanwhile,
475 the effect of the fraction of a month open to gag harvest positively impacted
476 angler-trips in the Peninsula but not the Panhandle. Furthermore, the lagged
477 gag and red grouper CPUE were positively associated with angler-trips in the
478 Peninsula, whereas such association was absent in the Panhandle. Finally,
479 discernible seasonal fluctuations in angler-trips also emerged, with distinct
480 variations observed in the effects of annual and semi-annual harmonic terms
481 between the Panhandle and the Peninsula. These findings underscore the sig-
482 nificance of integrating spatial and seasonal considerations when evaluating
483 recreational fishing effort patterns and resource utilization.

484 4. Discussion

485 The primary motivation of this study was to understand the effects of sea-
486 sonal management on multiple, highly sought-after species within the GOM
487 multispecies reef fishery. Our main finding, based on currently-available
488 recreational data, is that anglers targeting reef-fish are primarily respon-
489 sive to changes in red snapper and gag seasonal management. Given the
490 current, low estimated population sizes of gag, effects of seasonal manage-
491 ment for this species was a primary focus (SEDAR61 2018; SEDAR72 2021;
492 SEFSC 2022). Our results suggest additional limits to the fishing seasons
493 of gag will reduce recreational fishing effort directed towards reef fish in the
494 Florida Peninsula. These findings are particularly important given the re-
495 cent management actions undertaken for this species, which reduced the gag
496 recreational annual catch limit from 1,903,000 pounds in 2022 to 403,759
497 pounds in 2023 (nearly an 80% reduction) and reducing the recreational sea-
498 son from 214 to 49 days (Fig. 2). A key question confronted by managers was
499 whether drastic reductions in the gag season would result in effort concen-
500 trations during the open season such as that observed when the red snapper
501 seasons were reduced (Powers and Anson 2016, 2018; Farmer et al. 2020).
502 We did not find evidence that angler-trips increase in response to shortened
503 fishing seasons for this species, although we caution that more information
504 may be needed to conclusively determine that concentration effects will not
505 manifest at progressively narrower gag seasons.

506 *4.1. Regional drivers of Recreational Effort*

507 *4.1.1. Management effects*

508 Our results indicated that seasonal harvest management at the month
509 resolution influenced regional recreational effort. Monthly angler-trips in the
510 Panhandle increased as the fraction of a month open to fishing for red snap-
511 per increased, indicating that effort increased with increasing opportunities
512 to fish for this species (Trudeau et al. 2022). Similarly, the fraction of a
513 month open to harvest for gag meaningfully influenced effort the Peninsula.
514 Meanwhile, annual season length, conditioned on a given month being open
515 for harvest, influenced monthly effort in the Panhandle, but only for red
516 snapper. In other words, if a given month was open for red snapper har-
517 vest, angler-trips in that month were higher when the overall recreational
518 red snapper season was shorter (Fig. 5). This finding is consistent with
519 “effort concentration”, whereby anglers respond to shorter seasons by elect-
520 ing to fish for certain species more frequently in months which remain open
521 (Powers and Anson 2016, 2018; Farmer et al. 2020), but in this case only
522 appears to apply to red snapper. Notably, the effects of both red snapper
523 management predictors were considerably stronger in the Panhandle than the
524 Peninsula, which mirrors spatial patterns in red snapper distribution along
525 the west coast of Florida (e.g., SEFSC 2021), suggesting that recreational
526 anglers are more responsive to management changes to locally abundant reef
527 species. However, effort concentration was not apparent for gag. Although
528 the fraction of a month open to gag harvest positively influenced angler-
529 trips in the Peninsula, the length of the gag season did not affect monthly
530 angler-trips in either region. We expected a concentration (i.e., negative sea-
531 son length) effect in effort as red snapper seasons were reduced due to the
532 relatively limited length of red snapper recreational seasons in the last ten
533 years. In contrast, gag seasons were substantially longer. Between 2004 and
534 2023, 14 of 20 red snapper seasons were shorter than 100 days over the time
535 period studied, compared to only two gag seasons (Fig. 2). If anglers only
536 alter their behavior when season lengths are sufficiently short, historic gag
537 lengths may still be too long to detect a concentration effect, should one exist.
538 Consequently, given the current data available we cautiously conclude that
539 shorter gag recreational fishing seasons will reduce reef fish angler-trips in the
540 Peninsula, while underscoring that more information is needed to support our
541 results. Relatively short GOM gag recreational seasons are anticipated for
542 the foreseeable future as the stock rebuilds. Given this trend, future stud-

543 ies with similar frameworks will be crucial to conclusively determine that
544 effort concentration effects for this species do not exist as more information
545 becomes available.

546 *4.1.2. CPUE*

547 Lagged CPUE for both gag and red grouper meaningfully influenced
548 recreational effort in the Peninsula, while red snapper CPUE did not ap-
549 pear to influence recreational effort in either region. The positive effects of
550 CPUE in the Peninsula are consistent with the hypothesis that angler mo-
551 tivation to fish is influenced by the relative availability of prized species. In
552 addition, regional variation in these patterns likely reflects differences in long-
553 term availability as well as angler preferences. Both grouper species occur in
554 higher frequencies along the Peninsula and as a consequence the probability
555 of encountering legal-sized adults is much greater in this region (Grüss et al.
556 2017). Therefore, anglers may be more responsive to changes in the relative
557 abundance of grouper in regions where local abundance has historically been
558 high.

559 However, lagged CPUE did not influence the number of monthly angler-
560 trips for any species considered in the Panhandle. This was somewhat sur-
561 prising, particularly for red snapper, which is relatively more abundant along
562 the northern coast of the GoM (SEFSC 2021; Pollack 2021) and highly south-
563 after by recreational anglers (Garner and Patterson 2015; Powers and Anson
564 2016, 2018). One possible explanation for the absence of statistically mean-
565 ingful effects for this species may indicate that this species is targeted regard-
566 less of availability or that populations have not fallen to a point where anglers
567 noticeably change their behavior. Additionally, anglers may simply elect to
568 fish near reefs as long as CPUE from any reef species is sufficiently high to
569 make fishing a rewarding experience (Gundelund et al. 2022), particularly
570 given the high levels of investment anglers make when purchasing private ves-
571 sels and equipment. Moreover, other aspects of fishing which promote angler
572 satisfaction not investigated here, such as the size of fish caught or crowding
573 of local reef sites, may confound or mask effects of CPUE, should they exist
574 (Birdsong et al. 2021). Notably, these hypotheses are not mutually exclusive,
575 and each may in part explain these otherwise counter-intuitive results.

576 *4.1.3. Social and economic effects*

577 Neither annual saltwater fishing license sales nor the ratio of income to
578 fuel prices did not explain variation in effort in any region, although anglers

579 may react to these predictors in manners beyond the scope of our study. First,
580 information annual license sales was not region-specific, and as a consequence
581 if saltwater license purchases occurred in parts of Florida not considered in
582 this study, such as the east coast, it may mask the predictive power of this
583 variable. In addition, license sales do not account for lifetime licenses, and
584 as a result may not fully reflect the population of anglers. More granular
585 resolution, such as county-level license statistics by year, would improve un-
586 derstanding of the effect of this predictor on recreational effort in future
587 work. With respect to the income to fuel ratio, although higher fuel costs
588 have affected angler decisions in other systems (Chan et al. 2017; Pascoe et al.
589 2020), it is worth noting that the potential negative effect of fuel costs may
590 be counteracted or concealed by advancements in trip efficiency. The same
591 time frame when fuel prices were increasing coincided with the emergence
592 of more fuel-efficient engines, the integration of global positioning systems
593 with recreational vessels, and the adoption of fish-finding sonar technology.
594 These innovations likely curtailed the expenditure of fuel on scouting for or
595 relocating to favorable fishing locations, potentially lowering overall costs
596 and thereby encouraging fishing activities, even with increasing fuel prices.
597 Hence, a complex interplay of factors, beyond just income and fuel prices,
598 likely shapes the decisions of anglers (McCluskey and Lewison 2008), and
599 future studies exploring these associations in more detail may be helpful in
600 obtaining a more complete understanding of these factors.

601 *4.1.4. Seasonal effects*

602 Seasonality influenced monthly recreational effort in both regions, al-
603 though seasonal trends differed between the Panhandle and the Peninsula.
604 These patterns are likely at least partially a function of latitude, as the Pan-
605 handle is positioned north of the Peninsula (Fig. 1) and correspondingly ex-
606periences different oscillations in temperature and weather. Seasonal changes
607 in regional effort are also likely at least partially a function of species' activity
608 and position from shore throughout the year. For example, the semi-annual
609 periodicity in the Peninsula may be related to seasonal spawning behavior of
610 gag and red grouper. Mature female gag move into shallow waters in fall and
611 winter before spawning at deeper, offshore reefs in late winter (Koenig et al.
612 1996; Coleman et al. 2011; Grüss et al. 2017). Adult male gag remain in deep
613 waters year-round, while females return to nearshore areas for the remain-
614 der of the year (Coleman et al. 2011; Grüss et al. 2017; Lowerre-Barbieri
615 et al. 2020). Anecdotal reports from recreational and commercial anglers

616 also maintain that nearshore gag move to deeper waters in summer to avoid
617 higher summer water temperatures, although this behavior has not been re-
618 ported in scientific literature. Similarly, red grouper populations experience
619 seasonal patterns in availability due to spawning patterns (Coleman et al.
620 2011; Grüss et al. 2017). Statistically meaningful harmonic terms oscillat-
621 ing on semi-annual periodicity are consistent with such patterns, which were
622 more apparent in the Peninsula where grouper species are more abundant
623 (Grüss et al. 2017), although this term may capture the influence of other
624 seasonally-changing environmental variables. Future studies examining intra-
625 seasonal responses of gag and red grouper to shallow water temperature may
626 be helpful in clarifying these patterns. Finally, the monthly average wind
627 speed was not meaningfully associated with monthly effort in either region.
628 One explanation for the absence of a statistically discernible effect of wind on
629 recreational effort is the inclusion of harmonic regression terms. Wind speeds
630 exhibit seasonal periodicity, and inclusion of wind speed may not account for
631 additional variation in recreational effort after accounting for seasonal pat-
632 terns.

633 4.2. Caveats

634 Our findings lend insight into multiple regulatory, environmental, social,
635 and economic predictors of recreational effort in the multispecies reef fishery
636 along the west coast of Florida. However, there are important caveats to our
637 study that warrant consideration. First, our models are based on voluntary
638 survey data collected from public-access points. These survey data may not
639 accurately represent the recreational angler population using private docks,
640 thereby inserting non-response bias into the effort estimation (Fisher 1996),
641 but is common to most recreational surveys. Second, even if the data used
642 for our inferences are accurate, inherent observation uncertainty remains as a
643 result of incomplete sampling of the population (i.e., sampling error), which
644 was largely ignored in our analysis. Finally, although our models reliably
645 recaptured out-of-sample predictions from data withheld from the observed
646 time-series, we stress that predictions relying on extrapolations (i.e., forecasts
647 based on the same predictors whose values are outside the values observed in
648 this study), may be less accurate. A corollary to this caveat is that models
649 predicated on similar statistical frameworks will become increasingly accurate
650 and precise as future data with higher predictor contrast becomes available,
651 and thus we encourage the iterative application of this procedure to improve
652 management insights.

653 *4.3. Application and future work*

654 The analysis performed here underscores the complexity of effective man-
655 agement of recreational multispecies fisheries which dominate federal fisheries
656 in the Southeast USA. This study demonstrated the importance of consid-
657 ering the impacts of dominantly targeted species which may co-occur with
658 the target of management. Although helpful in clarifying general patterns in
659 recreational effort directed towards the multispecies reef fishery, future work
660 could build upon this study to improve management of this fishery.

661 First, concentration effects may manifest in aspects of recreational fishing
662 other than angler-trips. For example, anglers may be more likely to target
663 a given species (i.e., higher total catch given the same level of overall effort)
664 or a higher likelihood of retaining a fish for harvest (i.e., a higher proportion
665 of fish landed relative to all fish caught) when the season for that species
666 narrows. Such subtle changes in angler behavior are beyond the scope of this
667 study, but could be evaluated with models of catch and discard rates.

668 Second, although species-specific temporal closures can affect overall an-
669 gler effort, the degree to which management restrictions on one species will
670 impact fishing pressure on another likely varies by the pair of species consid-
671 ered and by region. For example, correlations between recreational gag and
672 red grouper catch rates are relatively strong (Farmer et al. 2016), suggesting
673 that temporal restrictions to harvest placed on grouper species may impact
674 fishing pressure on the other. In contrast, the degree of coupling between
675 gag and red snapper is less clear. Garner and Patterson (2015) observed
676 low rates of incidental gag catch among charter boats targeting red snapper,
677 but the charter boats considered operated in the western Florida Panhandle
678 and Alabama, where encounter probabilities of gag are low (Farmer et al.
679 2016; Grüss et al. 2017). Meanwhile, Farmer et al. (2016) also did not ob-
680 served highly correlated catch between red snapper and gag across the entire
681 northern GoM, but this may be due to differences in spatial extent. Red snap-
682 per are ubiquitous along the entire northern coastline of the GoM, whereas
683 gag spatial distributions are concentrated in GoM waters along the eastern
684 Florida Panhandle, Big Bend, and Peninsula (Farmer et al. 2016; Grüss et
685 al. 2017). Therefore, while our analysis suggests that shorter recreational
686 red snapper seasons would reduce recreational effort in the Panhandle, the
687 extent to which this reduction would alleviate gag fishing pressure in the
688 region remains uncertain. Given the differing spatial distributions of the
689 two species, it is likely that changes to red snapper seasons would not im-
690 pact gag fishing pressure as significantly as alterations to gag management

691 policies. Notably, these hypotheses can be rigorously evaluated by including
692 management variables pertaining to multiple species such as red snapper as
693 predictors in statistical models of CPUE. Research investigating these ef-
694 fects on highly sought-after, vulnerable species such as gag would be useful
695 in clarifying these relationships.

696 In summary, even if recreational effort is well understood, managers
697 should also consider bycatch and discard mortality rates to ensure that mod-
698 ifications intended to safeguard a vulnerable stock yield the intended results.
699 Therefore, the development of comprehensive modeling frameworks that inte-
700 grate angler effort dynamics, retention and bycatch rates, and discard mortal-
701 ity will be helpful in improving management. Similar to the statistical model
702 presented here, species-specific models of catch and discard rates should in-
703 clude management terms both for the species of interest as well as non-target
704 species to ensure that changes in angler behavior as a function of multispecies
705 management is taken into account.

706 **5. Acknowledgments**

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711 servancy.

712 Appendix A. Supplemental tables

Table S1: Predictor, coefficient, descriptions, and posterior summary statistics (median and 80% CI) included in the effort model (μ). Coefficient terms with asterisks denote posterior distributions of parameters that excluded 0 within their 80% CI. Gag = gag; RG = red grouper; RS = red snapper.

Predictor	Coefficient	Description	10%	50%	90%
<i>PH</i>	β_0^*	Intercept of mean (i.e. effect of Panhandle)	12.042	13.078	14.137
<i>PN</i>	β_1	Effect of Peninsula relative to reference intercept	-2.153	-0.748	0.576
<i>CPUE_{Gag}</i>	β_2	Effect of Gag CPUE in the Panhandle from the prior year	-0.052	0.131	0.324
<i>PN : CPUE_{Gag}</i>	β_3^*	Effect of Gag CPUE from prior year in the Peninsula relative to the Panhandle	0.142	0.415	0.683
<i>CPUE_{RG}</i>	β_4	Effect of RG CPUE from prior year in the Panhandle	-0.46	0.459	1.415
<i>PN : CPUE_{RG}</i>	β_5	Effect of RG CPUE from prior year in the Peninsula relative to the Panhandle	-1.298	-0.286	0.66
<i>CPUE_{RS}</i>	β_6	Effect of RS CPUE from prior year in the Panhandle	-0.134	0.389	0.926
<i>PN : CPUE_{RS}</i>	β_7	Effect of RS CPUE from prior year in the Peninsula relative to the Panhandle	-1.507	0.039	1.679
<i>Open_{Gag}</i>	β_8	Effect of the fraction of a month open to Gag harvest in the Panhandle	-2.102	-0.518	0.98
<i>PN : Open_{Gag}</i>	β_9^*	Effect of the fraction of a month open to Gag harvest in the Peninsula relative to the Panhandle	0.01	2.152	4.238
<i>Open_{RS}</i>	β_{10}^*	Effect of the fraction of a month open to RS harvest in the Panhandle	3.741	4.802	5.885
<i>PN : Open_{RS}</i>	β_{11}^*	Effect of the fraction of a month open to RS harvest in the Peninsula relative to the Panhandle	-6.264	-4.667	-3.184
<i>Season_{Gag}</i>	β_{12}	Effect of the log-length of the Gag season when Gag is open to harvest in the Panhandle	-0.17	0.103	0.393
<i>PN : Season_{Gag}</i>	β_{13}	Effect of the log-length of the Gag season when Gag is open to harvest in the Peninsula relative to the Panhandle	-0.747	-0.351	0.037
<i>Season_{RS}</i>	β_{14}^*	Effect of the log-length of the RS season when RS is open to harvest in the Panhandle	-1.158	-0.917	-0.7
<i>PN : Season_{RS}</i>	β_{15}^*	Effect of the log-length of the RS season when RS is open to harvest in the Peninsula relative to the Panhandle	0.551	0.866	1.183
<i>Sales</i>	β_{16}	Effect of the number of recreational 12 month saltwater fishing licenses sold in Florida from prior year in the Panhandle	-3.616	-1.499	0.54
<i>PN : Sales</i>	β_{17}^*	Effect of the number of recreational 12 month saltwater fishing licenses sold in the Peninsula relative to the Panhandle	0.567	3.133	5.962
<i>Ratio</i>	β_{18}	Effect of the income-fuel ratio (annual scale) in the Panhandle	-0.04	0.088	0.212
<i>PN : Ratio</i>	β_{19}	Effect of the income-fuel ratio (annual scale) in the Peninsula relative to the Panhandle	-0.282	-0.12	0.029
<i>Wind</i>	β_{20}	Effect of mean monthly wind speed in the Panhandle	-0.169	-0.037	0.1
<i>PN : Wind</i>	β_{21}	Effect of mean monthly wind speed in the Peninsula relative to the Panhandle	-0.196	-0.036	0.111
<i>sin₁₂</i>	β_{22}^*	Effect of the annual sinusoidal term (12-month periodicity) in the Panhandle	0.178	0.286	0.38
<i>PN : sin₁₂</i>	β_{23}	Effect of the annual sinusoidal term (12-month periodicity) in the Peninsula relative to the Panhandle	-0.177	-0.053	0.077
<i>cos₁₂</i>	β_{24}^*	Effect of the annual cosinusoidal term (12-month periodicity) in the Panhandle	-0.673	-0.517	-0.362
<i>PN : cos₁₂</i>	β_{25}^*	Effect of the annual cosinusoidal term (12-month periodicity) in the Peninsula relative to the Panhandle	0.298	0.487	0.664
<i>sin₆</i>	β_{26}	Effect of the semi-annual sinusoidal term (6-month periodicity) in the Panhandle	-0.114	-0.019	0.081
<i>PN : sin₆</i>	β_{27}	Effect of the semi-annual sinusoidal term (6-month periodicity) in the Peninsula relative to the Panhandle	-0.208	-0.089	0.032
<i>cos₆</i>	β_{28}	Effect of the semi-annual cosinusoidal term (6-month periodicity) in the Panhandle	-0.148	-0.026	0.089
<i>PN : cos₆</i>	β_{29}^*	Effect of the semi-annual cosinusoidal term (6-month periodicity) in the Peninsula relative to the Panhandle	0.08	0.214	0.361

Table S2: Predictor, coefficient, descriptions, and posterior summary statistics (median and 80% CI) included in the effort model (σ). Coefficient terms with asterisks denote posterior distributions of parameters that excluded 0 within their 80% CI.

Predictor	Coefficient	Description	10%	50%	90%
PH	ρ_0^*	Intercept of shape parameter (i.e. effect of Panhandle)	0.709	0.84	0.96
PN	ρ_1^*	Effect of Peninsula relative to reference intercept	0.402	0.581	0.766
\sin_{12}	ρ_2	Effect of the annual sinusoidal term (12-month periodicity) in the Panhandle	-0.247	-0.078	0.11
$PN : \sin_{12}$	ρ_3	Effect of the annual sinusoidal term (12-month periodicity) in the Peninsula relative to the Panhandle	-0.007	0.258	0.505
\cos_{12}	ρ_4^*	Effect of the annual cosinusoidal term (12-month periodicity) in the Panhandle	-1.005	-0.799	-0.598
$PN : \cos_{12}$	ρ_5^*	Effect of the annual cosinusoidal term (12-month periodicity) in the Peninsula relative to the Panhandle	0.172	0.441	0.725
\sin_6	ρ_6^*	Effect of the semi-annual sinusoidal term (6-month periodicity) in the Panhandle	-0.456	-0.248	-0.053
$PN : \sin_6$	ρ_7	Effect of the semi-annual sinusoidal term (6-month periodicity) in the Peninsula relative to the Panhandle	-0.222	0.038	0.317
\cos_6	ρ_8	Effect of the semi-annual cosinusoidal term (6-month periodicity) in the Panhandle	-0.314	-0.117	0.072
$PN : \cos_6$	ρ_9	Effect of the semi-annual cosinusoidal term (6-month periodicity) in the Peninsula relative to the Panhandle	-0.238	0.04	0.332

713 Appendix B. Supplemental Figures

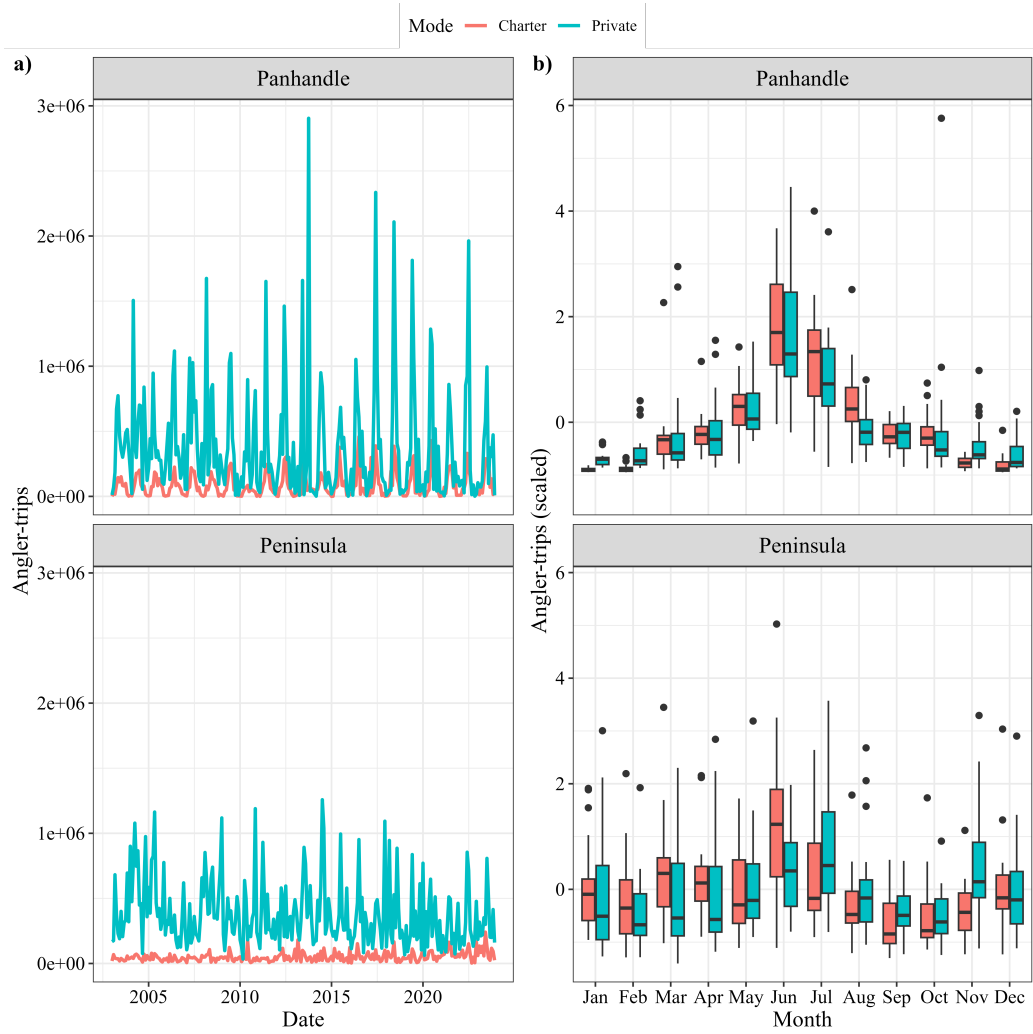


Figure S1: Comparisons of angler-trips by region and mode. Panel a) depicts time series of monthly angler-trips by region and mode, while panel b) depicts boxplots of angler-trips scaled (z-scored) by mode for each month.

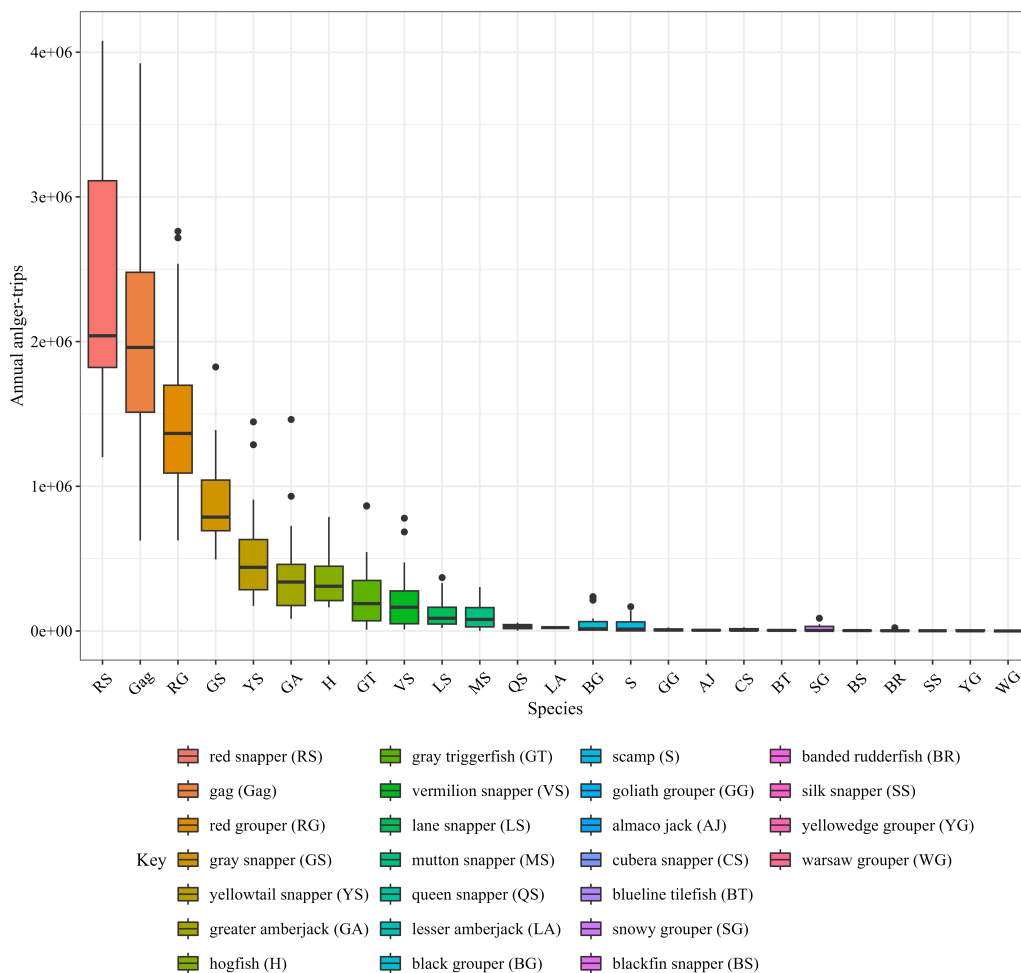


Figure S2: Boxplots of directed annual angler-trips among years for each species within the Gulf of Mexico reef fishery along the west coast of Florida based on MRIP data using NMFS OST 2023 estimation methodology. The spatial and temporal domains were Florida (Gulf of Mexico side) and annual, respectively. Note that several of the 31 species were not directly targeted and as a result are not included. Species are presented in order of decreasing median total annual estimated angler-trips between 2004 and 2023. Since anglers can specify both primary and secondary reef fish targets while also catching other reef fish in a single trip, there is inevitably some double-counting of trips. As a result, the sum of directed angler-trips among all species in each year is greater than the total number of directed angler-trips targeting any reef fish.

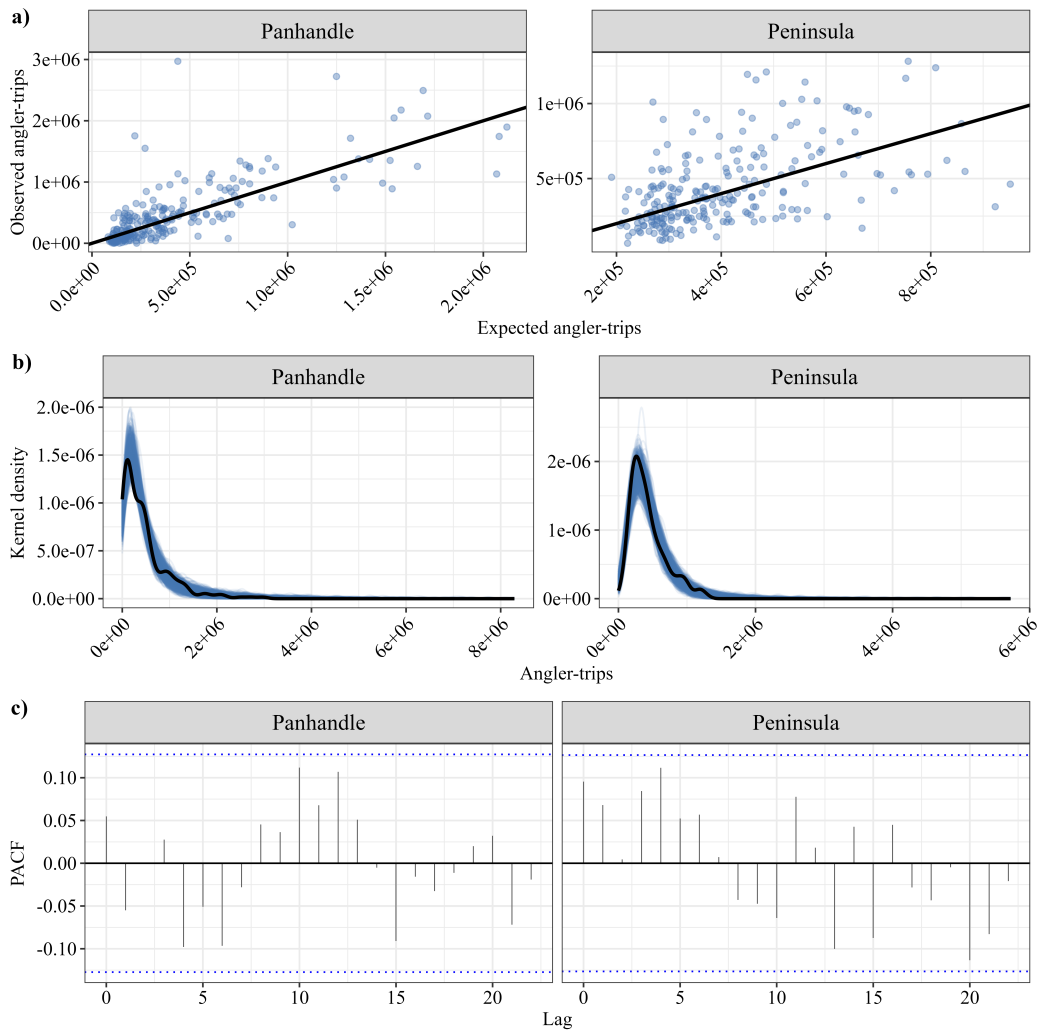


Figure S3: Diagnostic plots for the lognormal effort model. Panel a) depicts scatter plots of median predicted versus observed effort (angler-trips) for each region with the 1-1 line (black) superimposed for each region (i.e., Panhandle: left; Peninsula: right). Panel b) depicts the empirical distribution of observed angler-trips (black) to the distributions of 1000 scans from the posterior predictive distribution (blue) for each region. Finally, Panel c) depicts region-specific partial autocorrelation function (PACF) plots of median residuals using a model trained on the complete dataset (i.e., no withheld values) with a 95% confidence interval based on a normal distribution superimposed

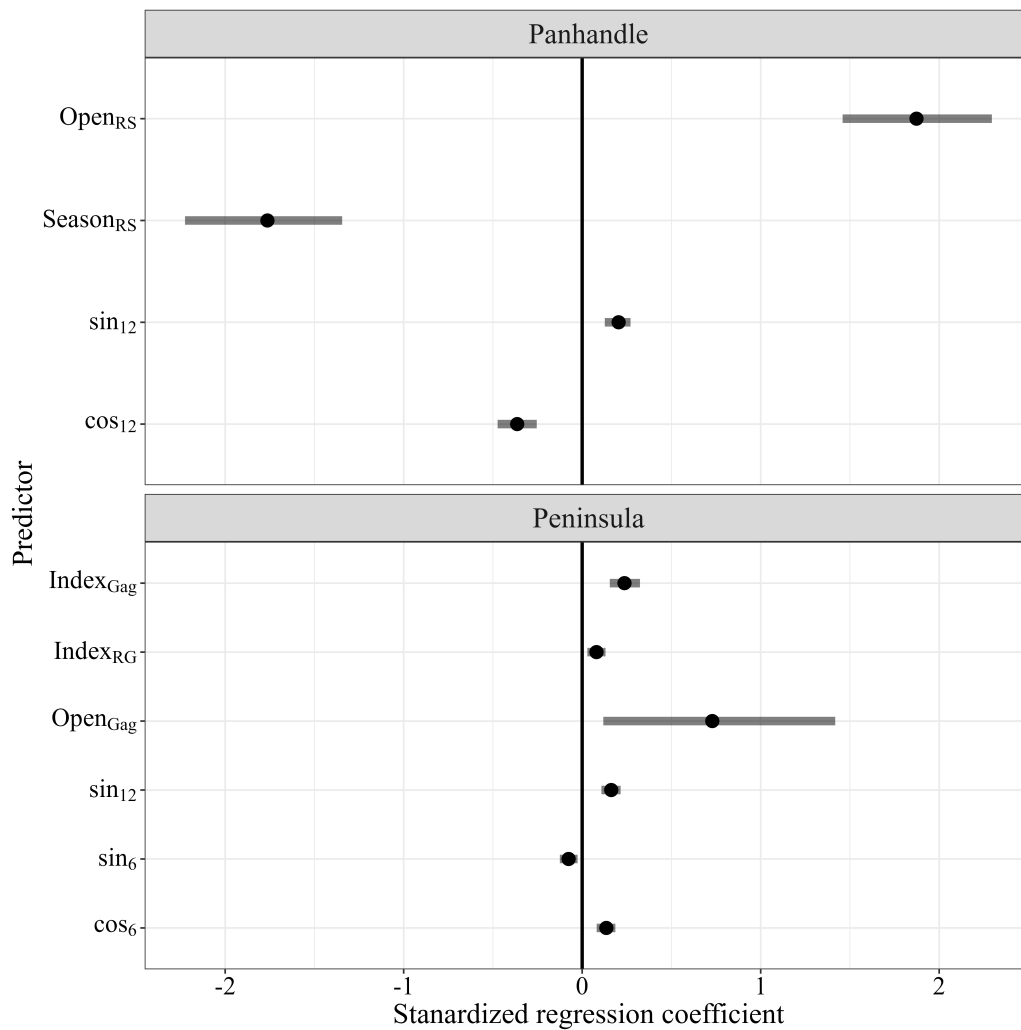


Figure S4: Posterior distributions (median and 80% CI) of standardized marginal effects whose 80% CIs excluded 0. Standardized posterior distributions of regression coefficients were estimated by multiplying the posterior distribution of each marginal effect by the region-specific standard deviation of its corresponding predictor.

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