Highlights

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

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- Red snapper and gag temporal management directly influenced recreational angler effort along the west coast of Florida
- The fraction of months open to harvest for both red snapper and gag were both positively associated with effort
- Red snapper season length was negatively associated with effort, suggesting effort concentration
- Gag grouper season length was not correlated with effort, suggesting effort concentration is not (yet) occurring for this species
Modeling effort in a multispecies recreational fishery; influence of species-specific temporal closures, relative abundance, and seasonality on monthly angler-trips

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\underline{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 (\textit{M. microlepis}), red grouper (\textit{E. morio}), and red snapper (\textit{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 sea-
sonal, 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.

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

1. Introduction

Effective management is a crucial component of sustainable fisheries.
Broadly speaking, fisheries are comprised of commercial and recreational
components, which are often regulated using different tactics. Commercial
fishing sectors are frequently managed using strict measures such as indi-
vidual fishing quotas, limited entry, or vessel monitoring systems (Anderson
et al. 2019), which are usually easier to monitor and regulate as landings are
often observed directly. In contrast, recreational fisheries present additional
management challenges (MacKenzie and Cox 2013; Bohaboy et al. 2022),
due in part to substantially larger numbers of individual recreational partici-
pants which must be indirectly sampled to monitor catch and effort, as well as
heterogeneity in the recreational fleet (e.g., Cox et al. 2002). In these cases,
seasonal harvest restrictions are a widely employed fishery management strat-
ey to alleviate recreational fishing pressure and achieve sustainable harvest.
Seasonal harvest closures are often aligned with spawning seasons to protect
or rebuild vulnerable species, and can be extended or shortened based on
stock status and catch levels (e.g., National Marine Fisheries Service 2022;
Gulf of Mexico Fishery Management Council 2023a,b). However, recreational
angler behavioral responses to seasonal closures are complex, poorly under-
stood, and often difficult to predict (e.g., Cox et al. 2002; Camp et al. 2016),
especially within the context of multispecies fisheries where multiple highly
sought-after species co-occur. Consequently, the effectiveness of seasonal
management regulations can be compromised or lead to deleterious effects
on one or more stocks should anglers respond in unexpected ways (Gentner
2004; Beaudreau et al. 2018; Abbott et al. 2018; Trudeau et al. 2022). Under-
standing how recreational angler dynamics respond to management changes
is therefore crucial for achieving long-term fisheries sustainability (Radom-
ski et al. 2001), especially for multispecies fisheries where incidental bycatch
cannot be avoided.

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

The Gulf of Mexico (GOM) multispecies reef fishery encompasses a di-
verse assemblage of 31 reef-associated finfish species, primarily managed with
seasonal restrictions (i.e., opening and closing dates), size limits, and catch
quotas that are species-specific. Commercial, for-hire, and recreational data
suggest this multispecies fishery is well mixed. Catch compositions of mul-
tiple species within the fishery tightly overlap, particularly notable among
species within respective shallow-water, mid-water, and deep-water snapper
and grouper complexes (Farmer et al. 2016). However, the degree of coupling
between specific species is dependent on the sector, gear, and region (Farmer
et al. 2016). Presently, two species – greater amberjack, *Seriola dumerili* and
gag, *Mycteroperca microlepis* (SEDAR70 2020; SEDAR72 2021) – are rec-
ognized as overfished (i.e., spawning stock biomass is too low), while other
species, including red grouper *Epinephelus morio*, have experienced recent population declines (SEDAR61 2018; SEFSC 2022). Depletion of multiple stocks and the limited recovery of others (e.g., greater amberjack; SEDAR70 2020) indicate that the restrictive regulations placed on these species have not reduced fishing mortality as expected, suggesting that a more nuanced management approach is required for this multispecies fishery (Chagaris et al. 2019). In particular, fishing mortality rates in the recreational sector have remained high, and the magnitude of regulatory discards can exceed directed harvest (Tetzlaff et al. 2013).

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

This study develops a statistical model to dissect the relationships between recreational fishing effort (measured in angler-trips) and species-specific seasonal management in the GOM along the west coast of Florida. We focused on ecological and management variables surrounding gag (*M. microlepis*), red grouper (*E. morio*), and red snapper (*Lutjanus campechanus*), which are the three most sought-after species recreationally in the west coast of Florida. Our central objectives were to identify and quantify the main drivers of regional effort along the west coast of Florida. Moreover, the declining stock size of one species – gag – led to major reductions in the most recent recreational harvest season (Gulf of Mexico Fishery Management Council 2023b), leading to concerns that such substantial reductions in season length might result in effort concentration for this species. Hence, we were especially interested in the effects of seasonal management for each species considered, where feasible, to understand how recreational reef fish effort responded to changes in these variables. In addition, we included environmental covariates such as seasonality and species-specific abundance as well as social and economic factors such as the number of saltwater fishing li-
cense sales, median household income, and fuel costs. Through this research, we aim to inform more effective management strategies within multispecies recreational fisheries.

2. Material and Methods

2.1. Survey data

We estimated monthly angler-trips (our proxy for angler effort) using survey data from the National Marine Fisheries Service (NMFS) Marine Recreational Information Program (MRIP). A main component of MRIP is the Access Point Angler Intercept Survey (APAIS), which is used to collect catch-per-trip data from anglers fishing from shore, private boats, and for-hire vessels based on in-person dockside interviews of anglers recently returning from a fishing trip. APAIS also collects information on location, distance from shore, primary and secondary target species, and other pertinent information as predictors modeling angler behavior. Dockside intercepts are weighted to extrapolate interviews to the population level using the Fishing Effort Survey (FES). Individual sample weights can be understood as the number of additional interviews that will be represented by the interview that was sampled (NMFS OST 2023). This weight is multiplied by the interview data collected through a particular questionnaire to determine weighted values (see MRIP estimation methods for more information). MRIP survey data prior to 2004 were not compatible with complex survey extrapolation techniques. As a result, we limited our focus to data from 2004 to 2023 (see the MRIP Recreational Fishing Data Downloads Guide for details). We also limited our consideration to APAIS interviews where anglers either declared at least one of the 31 reef species as a primary or secondary target or caught (retained or discarded) one of the 31 species. Finally, we only considered nearshore and offshore trips (i.e., no shoreline or beach trips), so that inferences were constrained to the reef fishery. As a result, only private vessel and charter trips were considered (accounting for 80% and 20% of all angler-trips considered, respectively, Fig. S1a). Monthly average angler-trips (scaled by mode) for each region suggested patterns among modes were similar (Fig. S1b). For all MRIP estimation procedures, we employed modified custom domain analyses templates using the the R language for statistical computing (R Core Team 2023) to aggregate FES-weighted angler-trips at varying temporal and spatial domains. To derive angler-trip estimates (effort), we took the product of the total number of anglers in a party and the sample
weight for each APAIS entry. For reproducibility, all modified templates and related estimation files are located in an online repository.

2.2. Species considered

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

2.3. Data aggregation

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

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

This aggregation resulted in a time-series comprising 240 monthly estimates (12 months x 20 years) in each region, although there were five missing
values (December in years 2006, 2014, 2018, 2019, and 2020) in the Panhan-
dle (235 estimates), amounting to a total of 475 estimates across both re-
gions. Notably, although this aggregation procedure is consistent with formal
MRIP templates designed to estimate mean fishing effort, it ignores observa-
tion uncertainty associated with incomplete sampling of the population (i.e.,
sampling error). Therefore we stress that some caution is warranted when
interpreting the results of these analyses due to the underlying imprecision
of our response variable.
2.4. Predictors

A combination of social, economic, environmental, and management variables (herein, predictors) were initially considered as potential determinants of recreational effort among regions. The following is a brief description of each predictor, the rationale for its consideration, and how the data were collected. Additional details on associated predictor symbology are in Table [8].

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

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

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

2.4.1. CPUE

Availability of harvestable fish is one fundamental driver of fishing effort. Higher availability of fish is positively linked to angler satisfaction due to higher associated catch-per-unit-effort (CPUE) (Arlinghaus and Mehner 2005; Arlinghaus 2006). Offshore fishing is a resource-intensive exercise re-
quiring time, fuel, and other indirect costs. If the expected CPUE is too low, the benefits of embarking on a recreational fishing trip may not outweigh the costs, and, as a result, fewer anglers may elect to fish (Cox et al. 2002; Post et al. 2003). Hence, we expected a generally positive relationship between CPUE and effort. Moreover, since anglers would conceivably base the decision to fish on past conditions, we expected effort would be related to CPUE in the previous year. For each region-month-year considered, we estimated CPUE for each species as the weighted average of all \( I \) CPUE estimates (defined as total fish caught divided by number of individuals in party from a given interview \( i \)) within that spatiotemporal unit:

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

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

2.4.2. Management

A common assumption in recreational fisheries management is that reductions in fishing season lengths result in decreased effort by reducing the number of opportunities to fish. To account for this, we included the fraction of a month open to fishing for a given species in each year within the time series. We expected that months with fewer days open (i.e., smaller fractions) would result in lower monthly angler-trips. On the other hand, evidence suggests that anglers may also compensate for shorter fishing seasons by embarking on more fishing trips when the season is open, resulting in effort concentration, particularly for highly sought-after species (Powers
and Anson 2016, 2018; Trudeau et al. 2022). Therefore, we also included
the length of each recreational fishing season as a predictor. We hypothe-
sized that shorter fishing seasons would result in higher effort in a given open
month relative to longer seasons (i.e., a negative effect).

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

In addition to environmental and management variables, variation in anthropogenic factors may also influence patterns in angler trips. Specifically, we expected the total number of saltwater anglers to positively influence the number of fishing trips taken in a given month. We assumed that annual 12-month Florida saltwater fishing license sales would be proportional to the saltwater angler population and used this variable as a proxy for angler abundance. Florida saltwater license sales were obtained from the Gulf States Marine Fisheries Commission [? ?]. Moreover, as trips to and from offshore reefs require considerable travel costs, we expected the price of fuel to be negatively associated with monthly effort (Chan et al. 2017; Pascoe et al. 2020; Farmer et al. 2020), and income to be positively associated with monthly effort. Importantly, income relative to fuel prices represents a reasonable proxy for financial resources available for discretionary spending, which we hypothesized would be an important economic influence on fishing effort. Therefore, we also included the ratio of Florida median income to fuel prices—both of which were adjusted for inflation a priori using the consumer price index (CPI; using 2023 dollars). Fuel price and CPI data were obtained from the U.S. Energy Information Administration 2023, and the U.S. Bureau of Labor Statistics 2023, respectively. Median Florida income was obtained through the U.S. Census Bureau 2022.

2.4.4. Weather

The decision to embark on a fishing trip is often dependent on weather conditions. Seasonal weather along Florida’s west coast is generally more favorable to fishing in summer and early fall. On a monthly scale, we hypothesized that recreational anglers would be less likely to fish if offshore wind conditions sufficiently high to the point of being hazardous. We included the mean wind speed (m/s) in each month as a predictor. Here, we obtained wind speed data from the NOAA National Data Buoy Center from 13 coastal buoys along the Florida Panhandle and western peninsular coastline (Fig. 1; U.S. Department of Commerce 2022, 2023j,i,h,b,k,g,d,c,f,e,a,l). These buoys were chosen for their location and associated data. Daily mean wind speeds were estimated from all buoys which had data available for a given day, which was subsequently averaged to obtain monthly average wind speed estimates for each region. This is in contrast to Farmer et al. (2020), which estimated the fraction of fishable days using both mean wind speeds and mean wave height. Unfortunately, wave height data for buoys considered...
in this study were only available after 2010, and only for select buoys in each region. Hence, we limited our consideration to wind speed, which tends to be correlated with wave height.

2.4.5. Seasonality

Harmonic regression terms were included as predictors to account for seasonal variation in angler behavior. Many species exhibit marked seasonal patterns in distribution and behavior. For example, many grouper species form seasonal spawning aggregations or otherwise exhibit seasonal movement related to spawning behavior (Koenig et al. 1996; Coleman et al. 2011; Grüss et al. 2017). Meanwhile, red snapper exhibit strong site fidelity to structured habitats, such as natural and artificial reefs (Topping and Szedlmayer 2011a), although movement in response to seasonal changes in environmental conditions are frequently reported (Topping and Szedlmayer 2011b; Switzer et al. 2015) and red snapper also tend to be more active in warmer months (Piraino and Szedlmayer 2014). Seasonal movement and aggregation behavior directly affects the vulnerability of these species to fishing pressure (e.g., Biggs et al. 2021) and may also influence intra-annual angler motivation to target a given species. To account for this, we included sinusoidal and cosinusoidal harmonic terms operating under two periods (annual and semi-annual) to account for the aforementioned seasonal patterns in distribution and availability (e.g., for the annual sinusoidal term, $\sin\left(\frac{2\pi m}{12}\right)$ where $m$ is a given month).

2.5. Analysis

We employed a gamma distribution to characterize the general reef fish effort in our modeling framework. Monthly angler-trip estimates, being positive with a lower bound of zero, exhibited a pronounced positive skewness. These distinctive characteristics rendered the gamma distribution an appropriate fitting choice for effectively describing this response variable. The complete effort model is therefore expressed as:
where $F_t$ denotes the number of angler-trips estimated in region-month-year $t$. Meanwhile, $\text{Gamma}(y|\alpha, \sigma)$ is the Gamma probability density function such that:

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

where $\alpha$ denotes the inverse-scale parameter, and $\sigma$ denotes the shape parameter, and $\Gamma(\cdot)$ denotes the Gamma function. The mean of the Gamma distribution, $\mu_t$, can be expressed as $\mu = \frac{\alpha}{\sigma}$. The ln mean $\mu_t$ is linearly related to an intercept ($\beta_0$) and set of $P$ linear predictors ($x_{t,1}, \ldots, x_{t,P}$) and corresponding coefficients ($\beta_1, \ldots, \beta_P$). Here, the shape parameter $\sigma_t$ is explicitly modeled based on intercept $\rho_0$ and linear predictors ($z_{t,1}, \ldots, z_{t,Q}$) based on our two regions and corresponding coefficients $\rho_1, \ldots, \rho_Q$ through a log-link function. These specifications relaxed the assumptions on variance in our modeling framework. The complete set of predictors and specific model coefficients are located in Tables S1 and S2. For model coefficients for both the mean structure ($\beta$) and error term ($\rho$), we supplied weakly informative priors with mean 0 and variance 100 to facilitate with model convergence.

### 2.5.1. Model implementation

All data analyses, transformations, and visualizations were carried out using the R programming language for statistical computing (R Core Team 2023) and the Stan probabilistic programming language for Bayesian statistical modeling (Gelman et al. 2015; Carpenter et al. 2017; Stan Development Team 2022) through the `brms` package (Bürkner 2017), leveraging
Hamiltonian Monte Carlo (HMC) sampling from the joint posterior. We ran four parallel Markov chains, each undergoing 1,000 iterations for the warm-up/adaptive phase and an additional 1,000 iterations to obtain posterior samples, resulting in a total of 4,000 draws for posterior inference. In terms of scientific relevance (i.e., significance), we focused on covariates and interactions whose posterior distributions excluded 0 within their 80% highest density probability interval (McElreath 2018), following the rationale provided in Hyman et al. 2022.

2.5.2. Temporal autocorrelation

In time series models, the temporal structure of the data often requires consideration because sequential estimates often do not represent independent replicates, as the presence of latent variables may introduce temporal autocorrelation. We initially considered a model with a similar structure that also included an AR(1) term. However, in- and out-of-sample fit were comparable among models with and without the AR(1) term, and partial autocorrelation plots did not indicate strong temporal autocorrelation among the residuals of the simpler model (Fig. S3c). Most notably, partial autocorrelation plots indicated that the inclusion of an AR(1) term did not appreciably reduce temporal autocorrelation (not shown). As a consequence, we considered the simpler model to be more appropriate under the principle of parsimony.

2.6. Marginal effects

We estimated marginal effects to evaluate the association between monthly angler-trips in each region and meaningful predictors while accounting for regional categorical effects. Opting for flexibility, we allowed the coefficients of all continuous predictors to vary across both MRIP regions. Consequently, the raw coefficient estimates for the Peninsula were determined in relation to the corresponding estimates for the Panhandle (our reference level). In other words, coefficients for the Peninsula are linear contrasts to the coefficient estimates for the Panhandle. Rather than presenting the Peninsula contrasts, we opted to directly report the region-specific intercept and continuous predictor coefficients. We summed correlated posterior draws from the reference coefficient of the Panhandle to the corresponding coefficients of the Peninsula. For instance, the effect of gag CPUE in the Peninsula was computed as the sum of the effect from the Panhandle and the effect from the Peninsula relative to the Panhandle ($\beta_{PN,CPUEGag} = \beta_2 + \beta_3$; Table S1), while
the marginal effect of gag CPUE in the Panhandle ($\beta_{PH,CPUE_{Gag}}$) is simply $\beta_2$. The marginal posterior distribution summary statistics utilize posterior median values and 80% confidence intervals.

2.7. **Conditional effects**

To conceptualize effort concentration with respect to progressively narrower fishing seasons, we developed conditional effects plots to depict the expected change in angler-trips in each region under a range of red snapper management conditions. Notable effort concentration was only apparent in red snapper management, and as a result we only focused on this species. First, we fixed all non-management covariates to conditional values. For each region, we conditioned Florida median income to fuel, and saltwater fishing license sales on monthly 2023 values, while conditional species-specific CPUE and wind speed was fixed at the region-specific, monthly averages among all years. Harmonic terms did not vary inter-annually and were simply fixed at their respective monthly values. To limit inference to a single month, we arbitrarily fixed the temporal window to the month of June. Next, we estimated the posterior predictive distribution of angler trips under total season lengths for red snapper ranging from 40 to 200 days (the minimum and maximum season length observed for red snapper, respectively) and fraction of the month open to harvest set at 0, 0.5, and 1. To isolate effects of management, we fixed the management values of all other species at zero. We subsequently calculated our season length variable as the log number of days open multiplied by the fraction of the month open to harvest (Section 2.4.2). Finally, we estimated the conditional posterior predictive distribution of angler-trips for each management combination (fraction of month open to harvest and season length variables) in each region. Conditional posterior predictive distributions of angler-trips here refer to the conditional expectation, $\mu_{cond}$, as a function of the entire joint posterior distribution of coefficients $\beta$ and a matrix of conditional predictors $X_{cond}$. Each conditional posterior predictive draw $d$ of the mean value $\mu_{cond}^{(d)}$ was estimated using the following equation:

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

(2)

where $\beta_p^{(d)}$ denotes the $d^{th}$ draw from the posterior predictive distribution of the $p^{th}$ predictor coefficient.
2.8. Out of sample predictions

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

3. Results

3.1. Model diagnostics

Time-series of observed versus predicted plots, diagnostic plots, and cross validation indicated that our statistical model was robust. Monthly angler-trip estimates for each region and uncertainty conformed with in-sample estimates of monthly angler-trips for both regions (Fig. 3). Moreover, diagnostic scatter-plots of median predicted versus observed reef fish effort suggested adequate model fit (Figs. S3a and S3b). Importantly, 87% and 82% of observed data withheld for out-of-sample cross validation fell within the nominal 80% posterior predictive intervals for the Panhandle and Peninsula, respectively (85% overall), suggesting that this model was also useful in forecasting future 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”).

3.2. Panhandle

In the Panhandle, nine of 20 predictors significantly explained variation in monthly angler-trips (Table 2). The fraction of the month open to red snapper harvest positively associated with monthly angler-trips, while red snapper season length was negatively associated with monthly angler-trips. Both the annual harmonic terms also explained variation in monthly angler-trips in the Panhandle. Finally, the annual cosinusoidal and semi-annual sinusoidal harmonic terms meaningfully impacted the shape parameter in the Panhandle.
Table 2: Posterior summary statistics (median and 80% CIs) for region-specific slope and intercept coefficients for \( \mu (\beta) \) and \( \sigma (\rho) \). 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.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Panhandle</th>
<th></th>
<th></th>
<th>Peninsula</th>
<th></th>
<th></th>
</tr>
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<tr>
<td></td>
<td>10%</td>
<td>50%</td>
<td>90%</td>
<td></td>
<td>10%</td>
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</tr>
<tr>
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<td>12.042</td>
<td>13.078</td>
<td>14.137</td>
<td>( \beta_{PN} )</td>
<td>11.494</td>
<td>12.318</td>
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<td>0.131</td>
<td>0.324</td>
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<td>0.554</td>
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<td>-0.7</td>
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<td>0.103</td>
</tr>
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<td>( \beta_{PN:Sales} )</td>
<td>-0.123</td>
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<td>( \beta_{Ratio} )</td>
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<td>0.088</td>
<td>0.212</td>
<td>( \beta_{PN:Ratio} )</td>
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<td>( \beta_{Wind} )</td>
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<tr>
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<td>0.089</td>
<td>( \beta_{PN:cos6} )</td>
<td>0.115</td>
<td>0.192</td>
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</table>

3.3. Peninsula

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

Expected angler-trips conditioned on predictor values outlined in Section 2.7, demonstrated the importance of red snapper management on angler trips in the Panhandle (Fig. 5). Under any given season length, expected effort was highest when the month was completely open to harvest and lowest when the month was completely closed (Open$_{RS}$ set to 1 and 0, respectively). However, differences in the conditional expectation among the fractions of the month open were considerably larger when the season was very short, whereas 80% CIs increasingly overlapped (suggesting statistical equivalence) under scenarios with progressively longer seasons. In contrast to the Panhandle, neither the fraction of the month open to red snapper nor red snapper season length had any effect on expected angler-trips (Table 2).
Figure 5: Conditional effects plots depicting the conditional expectation ($\mu_{\text{cond}}$) 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.

3.5. Comparisons among regions

Comparisons between regions revealed several statistically distinct spatial differences in the mean structure of the model (Tables 2, S1, and S2). Specif-
ically, in the Panhandle, the red snapper management terms exerted a much stronger influence on angler-trips than in the Peninsula (Fig. 5). Meanwhile, the effect of the fraction of a month open to gag harvest positively impacted angler-trips in the Peninsula but not the Panhandle. Furthermore, the lagged gag and red grouper CPUE were positively associated with angler-trips in the Peninsula, whereas such association was absent in the Panhandle. Finally, discernible seasonal fluctuations in angler-trips also emerged, with distinct variations observed in the effects of annual and semi-annual harmonic terms between the Panhandle and the Peninsula. These findings underscore the significance of integrating spatial and seasonal considerations when evaluating recreational fishing effort patterns and resource utilization.

4. Discussion

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

4.1.1. Management effects

Our results indicated that seasonal harvest management at the month resolution influenced regional recreational effort. Monthly angler-trips in the Panhandle increased as the fraction of a month open to fishing for red snapper increased, indicating that effort increased with increasing opportunities to fish for this species (Trudeau et al. 2022). Similarly, the fraction of a month open to harvest for gag meaningfully influenced effort the Peninsula. Meanwhile, annual season length, conditioned on a given month being open for harvest, influenced monthly effort in the Panhandle, but only for red snapper. In other words, if a given month was open for red snapper harvest, angler-trips in that month were higher when the overall recreational red snapper season was shorter (Fig. 5). This finding is consistent with "effort concentration", whereby anglers respond to shorter seasons by electing to fish for certain species more frequently in months which remain open (Powers and Anson 2016, 2018; Farmer et al. 2020), but in this case only appears to apply to red snapper. Notably, the effects of both red snapper management predictors were considerably stronger in the Panhandle than the Peninsula, which mirrors spatial patterns in red snapper distribution along the west coast of Florida (e.g., SEFSC 2021), suggesting that recreational anglers are more responsive to management changes to locally abundant reef species. However, effort concentration was not apparent for gag. Although the fraction of a month open to gag harvest positively influenced angler-trips in the Peninsula, the length of the gag season did not affect monthly angler-trips in either region. We expected a concentration (i.e., negative season length) effect in effort as red snapper seasons were reduced due to the relatively limited length of red snapper recreational seasons in the last ten years. In contrast, gag seasons were substantially longer. Between 2004 and 2023, 14 of 20 red snapper seasons were shorter than 100 days over the time period studied, compared to only two gag seasons (Fig. 2). If anglers only alter their behavior when season lengths are sufficiently short, historic gag lengths may still be too long to detect a concentration effect, should one exist. Consequently, given the current data available we cautiously conclude that shorter gag recreational fishing seasons will reduce reef fish angler-trips in the Peninsula, while underscoring that more information is needed to support our results. Relatively short GOM gag recreational seasons are anticipated for the foreseeable future as the stock rebuilds. Given this trend, future stud-
ies with similar frameworks will be crucial to conclusively determine that effort concentration effects for this species do not exist as more information becomes available.

4.1.2. CPUE

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

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

4.1.3. Social and economic effects

Neither annual saltwater fishing license sales nor the ratio of income to fuel prices did not explain variation in effort in any region, although anglers
may react to these predictors in manners beyond the scope of our study. First, information annual license sales was not region-specific, and as a consequence if saltwater license purchases occurred in parts of Florida not considered in this study, such as the east coast, it may mask the predictive power of this variable. In addition, license sales do not account for lifetime licenses, and as a result may not fully reflect the population of anglers. More granular resolution, such as county-level license statistics by year, would improve understanding of the effect of this predictor on recreational effort in future work. With respect to the income to fuel ratio, although higher fuel costs have affected angler decisions in other systems (Chan et al. 2017; Pascoe et al. 2020), it is worth noting that the potential negative effect of fuel costs may be counteracted or concealed by advancements in trip efficiency. The same time frame when fuel prices were increasing coincided with the emergence of more fuel-efficient engines, the integration of global positioning systems with recreational vessels, and the adoption of fish-finding sonar technology. These innovations likely curtailed the expenditure of fuel on scouting for or relocating to favorable fishing locations, potentially lowering overall costs and thereby encouraging fishing activities, even with increasing fuel prices. Hence, a complex interplay of factors, beyond just income and fuel prices, likely shapes the decisions of anglers (McCluskey and Lewison 2008), and future studies exploring these associations in more detail may be helpful in obtaining a more complete understanding of these factors.

4.1.4. Seasonal effects

Seasonality influenced monthly recreational effort in both regions, although seasonal trends differed between the Panhandle and the Peninsula. These patterns are likely at least partially a function of latitude, as the Panhandle is positioned north of the Peninsula (Fig. 1) and correspondingly experiences different oscillations in temperature and weather. Seasonal changes in regional effort are also likely at least partially a function of species’ activity and position from shore throughout the year. For example, the semi-annual periodicity in the Peninsula may be related to seasonal spawning behavior of gag and red grouper. Mature female gag move into shallow waters in fall and winter before spawning at deeper, offshore reefs in late winter (Koenig et al. 1996; Coleman et al. 2011; Grüss et al. 2017). Adult male gag remain in deep waters year-round, while females return to nearshore areas for the remainder of the year (Coleman et al. 2011; Grüss et al. 2017; Lowerre-Barbieri et al. 2020). Anecdotal reports from recreational and commercial anglers
also maintain that nearshore gag move to deeper waters in summer to avoid higher summer water temperatures, although this behavior has not been reported in scientific literature. Similarly, red grouper populations experience seasonal patterns in availability due to spawning patterns (Coleman et al. 2011; Grüss et al. 2017). Statistically meaningful harmonic terms oscillating on semi-annual periodicity are consistent with such patterns, which were more apparent in the Peninsula where grouper species are more abundant (Grüss et al. 2017), although this term may capture the influence of other seasonally-changing environmental variables. Future studies examining intra-seasonal responses of gag and red grouper to shallow water temperature may be helpful in clarifying these patterns. Finally, the monthly average wind speed was not meaningfully associated with monthly effort in either region. One explanation for the absence of a statistically discernible effect of wind on recreational effort is the inclusion of harmonic regression terms. Wind speeds exhibit seasonal periodicity, and inclusion of wind speed may not account for additional variation in recreational effort after accounting for seasonal patterns.

4.2. Caveats

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

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

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

Second, although species-specific temporal closures can affect overall angler effort, the degree to which management restrictions on one species will impact fishing pressure on another likely varies by the pair of species considered and by region. For example, correlations between recreational gag and red grouper catch rates are relatively strong (Farmer et al. 2016), suggesting that temporal restrictions to harvest placed on grouper species may impact fishing pressure on the other. In contrast, the degree of coupling between gag and red snapper is less clear. Garner and Patterson (2015) observed low rates of incidental gag catch among charter boats targeting red snapper, but the charter boats considered operated in the western Florida Panhandle and Alabama, where encounter probabilities of gag are low (Farmer et al. 2016; Grüss et al. 2017). Meanwhile, Farmer et al. (2016) also did not observed highly correlated catch between red snapper and gag across the entire northern GoM, but this may be due to differences in spatial extent. Red snapper are ubiquitous along the entire northern coastline of the GoM, whereas gag spatial distributions are concentrated in GoM waters along the eastern Florida Panhandle, Big Bend, and Peninsula (Farmer et al. 2016; Grüss et al. 2017). Therefore, while our analysis suggests that shorter recreational red snapper seasons would reduce recreational effort in the Panhandle, the extent to which this reduction would alleviate gag fishing pressure in the region remains uncertain. Given the differing spatial distributions of the two species, it is likely that changes to red snapper seasons would not impact gag fishing pressure as significantly as alterations to gag management.
policies. Notably, these hypotheses can be rigorously evaluated by including management variables pertaining to multiple species such as red snapper as predictors in statistical models of CPUE. Research investigating these effects on highly sought-after, vulnerable species such as gag would be useful in clarifying these relationships.

In summary, even if recreational effort is well understood, managers should also consider bycatch and discard mortality rates to ensure that modifications intended to safeguard a vulnerable stock yield the intended results. Therefore, the development of comprehensive modeling frameworks that integrate angler effort dynamics, retention and bycatch rates, and discard mortality will be helpful in improving management. Similar to the statistical model presented here, species-specific models of catch and discard rates should include management terms both for the species of interest as well as non-target species to ensure that changes in angler behavior as a function of multispecies management is taken into account.

5. Acknowledgments

This work was greatly improved by B Sauls and J Froeschke, whose helpful advice and suggestions greatly improved the scope and clarity of this study.

6. Funding

Preparation of this manuscript by ACH was funded by the Ocean Conservancy.
Table S1: Predictor, coefficient, descriptions, and posterior summary statistics (median and 80% CI) included in the effort model ($\mu$). Coefficient terms with asterisks denote posterior distributions of parameters that excluded 0 within their 80% CI. Gag = gag; RG = red grouper; RS = red snapper.

<table>
<thead>
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<th>Predictor</th>
<th>Coefficient</th>
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<th>50%</th>
<th>90%</th>
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<td>$\beta_2$</td>
<td>Effect of Gag CPUE in the Panhandle from the prior year</td>
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</tr>
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<td>Effect of the fraction of a month open to RS harvest in the Peninsula relative to the Panhandle</td>
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<td>0.103</td>
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<td>$PN \cdot$ Season$_{RS}$</td>
<td>$\beta_{15}$</td>
<td>Effect of the log-length of the RS season when RS is open to harvest in the Peninsula relative to the Panhandle</td>
<td>0.551</td>
<td>0.866</td>
<td>1.183</td>
</tr>
<tr>
<td>Sales</td>
<td>$\beta_{16}$</td>
<td>Effect of the number of recreational 12 month saltwater fishing licenses sold in Florida from prior year in the Panhandle</td>
<td>-3.616</td>
<td>-1.499</td>
<td>0.54</td>
</tr>
<tr>
<td>$PN \cdot$ Sales</td>
<td>$\beta_{17}$</td>
<td>Effect of the number of recreational 12 month saltwater fishing licenses sold in the Peninsula relative to the Panhandle</td>
<td>0.567</td>
<td>3.133</td>
<td>5.962</td>
</tr>
<tr>
<td>Ratio</td>
<td>$\beta_{18}$</td>
<td>Effect of the income-fuel ratio (annual scale) in the Panhandle</td>
<td>-0.04</td>
<td>0.088</td>
<td>0.212</td>
</tr>
<tr>
<td>$PN \cdot$ Ratio</td>
<td>$\beta_{19}$</td>
<td>Effect of the income-fuel ratio (annual scale) in the Peninsula relative to the Panhandle</td>
<td>-0.282</td>
<td>-0.12</td>
<td>0.029</td>
</tr>
<tr>
<td>Wind</td>
<td>$\beta_{20}$</td>
<td>Effect of mean monthly wind speed in the Panhandle</td>
<td>-0.169</td>
<td>-0.037</td>
<td>0.1</td>
</tr>
<tr>
<td>$PN \cdot$ Wind</td>
<td>$\beta_{21}$</td>
<td>Effect of mean monthly wind speed in the Peninsula relative to the Panhandle</td>
<td>-0.196</td>
<td>-0.036</td>
<td>0.111</td>
</tr>
<tr>
<td>sin$_{12}$</td>
<td>$\beta_{22}$</td>
<td>Effect of the annual sinusoidal term (12-month periodicity) in the Panhandle</td>
<td>0.187</td>
<td>0.286</td>
<td>0.38</td>
</tr>
<tr>
<td>$PN \cdot$ sin$_{12}$</td>
<td>$\beta_{23}$</td>
<td>Effect of the annual sinusoidal term (12-month periodicity) in the Peninsula relative to the Panhandle</td>
<td>-0.177</td>
<td>-0.053</td>
<td>0.077</td>
</tr>
<tr>
<td>cos$_{12}$</td>
<td>$\beta_{24}$</td>
<td>Effect of the annual cosinusoidal term (12-month periodicity) in the Panhandle</td>
<td>-0.673</td>
<td>-0.517</td>
<td>-0.362</td>
</tr>
<tr>
<td>$PN \cdot$ cos$_{12}$</td>
<td>$\beta_{25}$</td>
<td>Effect of the annual cosinusoidal term (12-month periodicity) in the Peninsula relative to the Panhandle</td>
<td>0.298</td>
<td>0.487</td>
<td>0.664</td>
</tr>
<tr>
<td>sin$_{6}$</td>
<td>$\beta_{26}$</td>
<td>Effect of the semi-annual sinusoidal term (6-month periodicity) in the Panhandle</td>
<td>-0.114</td>
<td>-0.019</td>
<td>0.083</td>
</tr>
<tr>
<td>$PN \cdot$ sin$_{6}$</td>
<td>$\beta_{27}$</td>
<td>Effect of the semi-annual sinusoidal term (6-month periodicity) in the Peninsula relative to the Panhandle</td>
<td>-0.208</td>
<td>-0.089</td>
<td>0.032</td>
</tr>
<tr>
<td>cos$_{6}$</td>
<td>$\beta_{28}$</td>
<td>Effect of the semi-annual cosinusoidal term (6-month periodicity) in the Panhandle</td>
<td>-0.148</td>
<td>-0.026</td>
<td>0.089</td>
</tr>
<tr>
<td>$PN \cdot$ cos$_{6}$</td>
<td>$\beta_{29}$</td>
<td>Effect of the semi-annual cosinusoidal term (6-month periodicity) in the Peninsula relative to the Panhandle</td>
<td>0.08</td>
<td>0.214</td>
<td>0.361</td>
</tr>
</tbody>
</table>
Table S2: Predictor, coefficient, descriptions, and posterior summary statistics (median and 80% CI) included in the effort model ($\sigma$). Coefficient terms with asterisks denote posterior distributions of parameters that excluded 0 within their 80% CI.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coefficient</th>
<th>Description</th>
<th>10%</th>
<th>50%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PH</td>
<td>$\beta_0$</td>
<td>Intercept of shape parameter (i.e. effect of Panhandle)</td>
<td>0.709</td>
<td>0.84</td>
<td>0.98</td>
</tr>
<tr>
<td>PN</td>
<td>$\beta_1$</td>
<td>Effect of Peninsula relative to reference intercept</td>
<td>0.402</td>
<td>0.581</td>
<td>0.766</td>
</tr>
<tr>
<td>$\sin_{12}$</td>
<td>$\beta_2$</td>
<td>Effect of the annual sinusoidal term (12-month periodicity) in the Panhandle</td>
<td>-0.247</td>
<td>-0.078</td>
<td>0.11</td>
</tr>
<tr>
<td>$PN : \sin_{12}$</td>
<td>$\beta_3$</td>
<td>Effect of the annual sinusoidal term (12-month periodicity) in the Peninsula relative to the Panhandle</td>
<td>-0.087</td>
<td>0.258</td>
<td>0.505</td>
</tr>
<tr>
<td>$\cos_{12}$</td>
<td>$\beta_4$</td>
<td>Effect of the annual cosineoidal term (12-month periodicity) in the Panhandle</td>
<td>-1.065</td>
<td>-0.799</td>
<td>-0.598</td>
</tr>
<tr>
<td>$PN : \cos_{12}$</td>
<td>$\beta_5$</td>
<td>Effect of the annual cosineoidal term (12-month periodicity) in the Peninsula relative to the Panhandle</td>
<td>0.172</td>
<td>0.441</td>
<td>0.725</td>
</tr>
<tr>
<td>$\sin_{6}$</td>
<td>$\beta_6$</td>
<td>Effect of the semi-annual sinusoidal term (6-month periodicity) in the Panhandle</td>
<td>-0.456</td>
<td>-0.248</td>
<td>-0.053</td>
</tr>
<tr>
<td>$PN : \sin_{6}$</td>
<td>$\beta_7$</td>
<td>Effect of the semi-annual sinusoidal term (6-month periodicity) in the Peninsula relative to the Panhandle</td>
<td>-0.222</td>
<td>0.038</td>
<td>0.317</td>
</tr>
<tr>
<td>$\cos_{6}$</td>
<td>$\beta_8$</td>
<td>Effect of the semi-annual cosineoidal term (6-month periodicity) in the Panhandle</td>
<td>-0.314</td>
<td>-0.117</td>
<td>0.072</td>
</tr>
<tr>
<td>$PN : \cos_{6}$</td>
<td>$\beta_9$</td>
<td>Effect of the semi-annual cosineoidal term (6-month periodicity) in the Peninsula relative to the Panhandle</td>
<td>-0.238</td>
<td>0.04</td>
<td>0.332</td>
</tr>
</tbody>
</table>
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.

References

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