Chapter 3: Lower possession limits and shorter seasons directly reduce for-hire fishing effort in a multispecies marine recreational fishery

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Abstract

Managers of recreational fisheries often rely on implicit and rarely-tested assumptions regarding how fishing effort will change in response to regulations. For instance, they assume that reduced seasons will directly reduce fishing effort without producing angler behavioral adaptations to maintain fishing opportunities and harvest. Vessel trip reports from a multispecies for-hire fishery in New Jersey, USA allowed us to empirically evaluate changes in fishing effort as overlapping seasons for four species became shorter and as possession limits decreased. We conducted focus groups with fishery stakeholders and then developed statistical models to evaluate hypotheses describing how anglers aboard for-hire vessels adapted to regulations. Fishing effort aboard charter boats remained consistent and primarily responded to the availability of "something" to harvest, suggesting that their customers are willing to substitute target species. Party boat anglers, in contrast, responded to the possession limits of black sea bass (*Centropristis striata)*, and summer flounder (*Paralichthys dentatus*). Because party anglers were

less willing to substitute target species, party vessel operators are likely particularly vulnerable to reductions in fishing opportunity and harvest potential.

Introduction

Recreational fisheries management worldwide struggles to limit harvest while concurrently meeting biological and socioeconomic objectives (Cox et al. 2002; Post et al. 2002; Abbott et al. 2018). Fisheries managers set and tune regulations such as season length, possession limits, and size limits to meet recreational harvest quotas, but angler response to these management changes is poorly understood. Anglers may adjust their behavior to compensate for new restrictions (e.g. Beaudreau et al. 2018; Gentner 2004; Powers and Anson 2018), or they may choose to leave the fishery (e.g. Holzer and McConnell 2017; Mackay et al. 2020; Whitehead et al. 2015). Restrictive regulations may not result in the expected reduction in harvest in the presence of compensatory behavior. Conversely, declining participation in the fishery can harm coastal communities that rely on income from the recreational fishing industry (Chan et al. 2018; Murray et al. 2010; NMFS 2018). Further complicating this calculation, in multispecies fisheries, anglers may switch targets when regulations are no longer acceptable to them (Beaudreau et al. 2018). This may be a desirable outcome if it relieves pressure on threatened stocks, but these alternative targets may then be subject to enough harvest pressure to become depleted (Abbott et al. 2018). Whereas fisheries managers can frequently monitor commercial harvest throughout the season (e.g. Gerritsen and Lordan 2011; Lee et al. 2010), recreational fisheries managers generally have few options for monitoring harvest or making changes mid-season (Pereira and Hansen 2003). An empirical understanding of the link between fishing regulations and resulting fishing effort is therefore needed to better inform fisheries management choices.

Regulations have the potential to reduce the utility that anglers receive from fishing, but their effects depend on individual preferences. Recreational anglers place value on catch (i.e. the number of fish kept and released), harvest (i.e. the number of fish kept), and the overall fishing experience (Hunt et al. 2019). Throughout this paper, we will use “catch” to indicate all fish caught, including those kept and released, while “harvest” refers only to fish that are caught and kept. In a utility-maximizing approach to understanding angler decisions, the choice of whether or not to fish will depend on whether the expected fishing experience, catch, and harvest provide enough utility to outweigh the cost in time and money incurred by taking the trip (e.g. McFadden 1974). Reductions in season length do not necessarily reduce the value of fishing trips, but they narrow the window of opportunity for anglers to schedule their fishing trips. This loss of opportunity potentially results in the loss of benefits related to the overall fishing experience if, for instance, inclement weather cancellations are proportionally more common. Reduced possession limits, in contrast, may reduce the benefits anglers receive from harvest itself. Anglers may still catch a lot of fish, which may still be satisfying to individuals who are highly catch-oriented (e.g. Schroeder and Fulton 2013). However, the lower possession limit places a ceiling on the harvest that anglers can take home, meaning that anglers who primarily fish for food may no longer decide to take the trip. Since the experience of the fishing trip is still valued by many anglers regardless of catch, however, fishing effort can remain highly elastic to regulations, depending on angler preferences (e.g. Beardmore et al. 2011a). When anglers do leave the fishery as a result of benefit loss associated with restrictive regulations, coastal communities experience negative economic effects as vessel operators and other businesses associated with the recreational fishery lose revenue (NMFS 2018). Understanding these potential angler responses therefore allows fisheries managers to weigh tradeoffs in the biological, social, and economic outcomes of their decisions.

Much uncertainty therefore exists when predicting how recreational fishing effort, and therefore harvest, will respond to changes in regulations. This uncertainty arises in part from unknowns associated with angler behavior, motivations, and preferences (e.g. Brinson and Wallmo 2017; Johnston et al. 2010). While anglers tend to express preferences for longer open seasons (Holzer and McConnell 2017; Young et al. 2019; Melnychuk et al. 2021), shorter seasons do not necessarily cause anglers to reduce their fishing effort. For example, during extreme reductions in season length for the red snapper (*Lutjanus campechanus*) fishery in the Gulf of Mexico, daily angler effort substantially increased, leading to a "derby style" fishery where private anglers, who own or rent their own boats, attempted to fish as much possible during their allotted time (Powers and Anson 2018, 2016). Shorter seasons therefore still corresponded to lower harvest across the season, but not in proportion to the change in season length. Because the functional response of fishing effort to shorter seasons is not often quantified and likely varies widely by fishery, this "effort compression" effect complicates managers' predictions of the response of harvest to changes in regulations. Further, reductions in possession limits can reduce the attractiveness of fishing opportunities to anglers (Whitehead et al. 2015), but angling effort in different fisheries may show different degrees of elasticity to changes in these regulations (Beard et al. 2003; Beardmore et al. 2011a) and may therefore not substantially affect overall harvest (van Poorten et al. 2013). In fisheries where open seasons overlap for multiple species, predicting angler response is further complicated. For example, in the multispecies for-hire recreational fisheries in Alaska, increased restrictions on harvest of Pacific halibut (*Hippoglossus stenolepis*) has been associated with increased harvest of less restricted species (Beaudreau et al. 2018). This substitution behavior can lead to a continuous "spiraling" effect of regulations where managers implement increasingly strict limits on an increasing variety of species, and anglers continue to adapt by diversifying their targets in order to maintain their harvest (Abbott et al. 2018; Beaudreau et al. 2018). The effects of regulations on fishing effort may therefore depend on how anglers and operators of for-hire vessels respond to fishing opportunity (i.e. season length), harvest potential per trip (i.e. possession limit or variety of species available), and preferences for specific species (e.g. the popularity of species among harvest- or trophy-oriented anglers).

Because of this uncertainty in angler response to regulation, managers of open-access fisheries have not always successfully kept removals below sustainable harvest limits (Coleman et al. 2004; Cooke and Cowx 2004; Cox et al. 2002; Post et al. 2002; NEFSC 2019). This inconsistency in constraining recreational harvest points to a need for empirically understanding the effects of regulations on fishing effort in a multispecies context. Forecasting and "nowcasting" techniques have already been successfully used to predict landings in the Gulf of Mexico recreational fishery for individual species (Carter et al. 2015; Farmer and Froeschke 2015), but not to infer the effects of multiple species' regulations on fishing effort. By understanding the dynamics of both catch and effort in response to regulations, managers can reduce the uncertainty around how changes in season length of multiple (or individual) seasons in multi-species fisheries will affect fishing effort.

The Marine Recreational Information Program (MRIP) produces estimates of recreational catch and effort for most coastal states. Estimates are aggregated by two-month "waves" or by year. More granular estimates of fishing effort, however can be difficult and expensive to obtain in recreational fisheries (McCluskey and Lewison 2008), but Vessel Trip Report (VTR) data provide a daily census count of recreational fishing effort aboard federally-permitted for-hire vessels in the Greater Atlantic Region. We then empirically evaluated the response of weekly fishing effort to changes in possession limits, season length, and season overlap in the New Jersey (NJ), USA, for-hire sector of the bottom fishery using this VTR data. To do this, we fit statistical models incorporating effects of four species' overlapping open seasons, their season lengths, and the number of "blackout" days during which none of the four species are available to harvest to a time series of weekly fishing effort. Guided by hypotheses formulated through focus-group interviews with stakeholders, a model selection process allowed us to infer the dominant mechanisms by which changes in possession limits, season length, and species availability could have influenced overall fishing effort in the NJ for-hire bottom fishery. Differences in overall preferences between anglers participating in the charter and party boat fisheries were inferred by fitting these models to time series separately for each sector.

The New Jersey bottom fishery is primarily harvest-motivated (e.g. Bochenek et al. 2012), so we hypothesized that lower possession limits for popular species would be associated with a reduction in angler trips in a given week. While lower possession limits reduce the harvest potential of single fishing trips, shorter and more fragmented fishing seasons instead limit angler access to the fishery. During closed seasons, no targeting of any affected species is permitted, even for catch and release angling. Shorter seasons therefore leave fewer days available to fish for a given species each year, and reduced overlap of these seasons may limit the variety of fish that an angler is allowed to catch and harvest. Reductions in fishery access through shortened seasons has historically been assumed to have a direct effect on fishing effort, where angling trips that would have taken place during the now-closed season simply do not occur. We hypothesized that reductions in fishing effort associated with shorter seasons may instead be lower or higher than expected depending on whether anglers tended to respond to benefit loss associated with regulatory change by either 1) compensating for reduced fishing opportunity or 2) reducing their participation in the fishery. Of course, angler response to these changes in regulations will be heterogeneous because their responses depend on motivations and preferences that vary among anglers (e.g. Beardmore et al. 2011b). If particular responses dominate angler effort dynamics, however, the overall effect on all angler effort will be useful in a broad-scale policymaking context. We conducted a time series analysis of weekly total angler trips from the recreational for-hire sector in NJ to test the following hypotheses derived from focus group data describing how anglers may have adapted to changes in fishing opportunity:

1) *Species availability hypothesis*: Anglers switch between preferred species to maintain their opportunities to go fishing.

2) *Season length hypothesis*: Anglers intensify their fishing effort during shorter open seasons to maintain their preferred harvest levels.

3) *Blackout effect hypothesis*: In response to an increasing number of "blackout" days, where neither of these four bottomfish are available for harvest, anglers will either a.) increase their fishing effort during the remaining open seasons or b.) begin to exit the fishery.

Methods

Study system

The NJ marine recreational fishery is socioeconomically important, ranking fourth in the nation in state sales revenue generated by the recreational fishing industry (NMFS 2018). NJ anglers are also responsible for substantial removals, ranking second among US states in pounds of recreational harvest and fourth in release numbers (NMFS 2020). The for-hire sector makes up between 5 and 20% of total recreational catch, depending on the species, while the remaining catch is made up by shore-based anglers and private anglers who own or rent their own boats (ASMFC 2017; MAFMC and ASMFC 2020). The for-hire fleet is made up of party boats (also called head boats), where anglers pay between $30 and $90 “per head” for a 4-8 hour guided trip shared with up to 100 other anglers, and charter boats, where a smaller group of anglers (typically 6 or fewer) pays more, currently between $400 and $1000, for a more personalized guided fishing trip on a smaller vessel (Steinback and Brinson, 2013). For-hire fishing vessels are highly accessible. Anglers may borrow or rent fishing gear, and no additional licensing or registration is required to participate. Spending by out-of-state anglers is particularly impactful in the for-hire fishing industry, and fishing effort by these anglers in this sector is sensitive to changes in fares (Li et al. 2019; Steinback 1999). As overhead costs (e.g. fuel, bait, boat maintenance) increase among for-hire operators as a result of fuel prices and reduced season lengths, businesses and communities relying on revenue from this sector are increasingly vulnerable to volatility in angler numbers which could result from regulatory changes (Murray et al. 2010).

As fisheries managers have struggled to limit harvest in order to maintain or rebuild fish stocks, the NJ marine recreational fishery has experienced marked changes in possession limits and season lengths for summer flounder (*Paralichthys dentatus*), black sea bass (*Centropristis striata*), scup (*Stenotomus chrisops*), and tautog (*Tautoga onitis*) (Fig. 1, Tables S1-S4). In spite of these changes, black sea bass recreational harvest in recent years (2013-2017) has exceeded harvest limits by an average of 41% (MAFMC 2018), and tautog continues to be classified as overfished (ASMFC 2007; ASMFC 2017). Although summer flounder was not overfished as of the latest stock assessment (NEFSC 2019), changes in distribution, reductions in recruitment, upward corrections of previous years' harvest estimates, and a strict fisheries management plan have led to the continuation of stringent harvest regulations (ASMFC 2018; Terceiro 2018). Summer flounder is a highly popular target species in the NJ marine recreational fishery, and the resulting short and fragmented seasons in the face of perceived improvement in the summer flounder stock have led to widespread frustration among stakeholders (Terceiro 2018). Tautog season lengths were reduced in 2008 in response to overfishing in the recreational sector (ASMFC 2007). In spite of the rebuilding plan implemented at this time, tautog spawning stock biomass remains low, and the stock is classified as overfished (ASMFC 2017). In contrast, a fisheries management plan for scup that was implemented in 1998 and amended in 2007 was successful in reducing harvest, and the stock was declared recovered in 2009 (MAFMC and NMFS 2007; Northeast Data Poor Stocks Working Group 2009).

Focus groups

Four focus groups were conducted across a north-south transect of the NJ coast in the towns of Atlantic Highlands, Toms River, Tuckerton, and Cape May in the winter and spring of 2019. Participants were identified through purposive sampling in which researchers consulted with NJ state agency staff, extension agents, and industry representatives to identify knowledgeable, experienced, and collaborative recreational fishing industry stakeholders. Two to four stakeholders from each of four industry segments (party boats, charter boats, private anglers who own their own boats or fish from shore, and associated businesses) in each of the four regions were identified, for a potential maximum of 16 participants per focus group. Of these, 44 stakeholders were successfully contacted and invited, and 37 attended. The focus groups ranged from 8 to 11 participants, plus two note takers and a moderator, and they lasted between two and two and a half hours. Focus group participants were asked open-ended questions about their process for choosing bottomfish target species and how those decisions are influenced by management regulations and their clients' or their own personal preferences. All focus groups were audio recorded, transcribed, and coded for common themes, following the standard analysis guidelines for qualitative research in Creswell and Poth (2016) and Roller and Lavrakas (2015). The focus group procedure was approved by the Rutgers Institutional Review Board (Protocol #E18-112).

Results from the focus groups were used to develop alternative hypotheses to be tested in the analysis of VTR data. Overall, recreational industry representatives expressed strong dissatisfaction with current regulations, especially season length and timing. As one focus group participant said, "What I've observed here is just absolute, total frustration, bordering on anger. And I keep saying to myself, these regulations are going to turn a lot of local fishermen to pirates." Of particular concern to stakeholders were the partitioning of open seasons into shorter periods and the loss of overlapping seasons for different species (Table S5). A common point that stakeholders discussed was that the loss of overlap between different species' open seasons was leading anglers to intensively harvest whatever species remained open at a given time. Two possible mechanisms for this change in behavior were incorporated into the hypotheses for our model selection: 1) anglers maintain harvest potential by compressing fishing effort into shorter seasons to maintain harvest of particular species or 2) anglers switch target species in order to continue fishing on a consistent basis.

Effort, catch, and management data

Vessel Trip Report (VTR) data from for-hire vessels between 2001 and 2017 were obtained from the NOAA VTR database for the Greater Atlantic region. VTRs are a census of vessels with federal permits for black sea bass, summer flounder, or scup where operators report the number of anglers aboard and enumerate their catch and harvest. VTR data from 2018 and 2019 were not included in the analysis because the 2018 switch to mandated electronic reporting may have resulted in a systematic change in reporting compliance. VTRs do not report target species, so data were filtered according to the vessels' port state and the species they reported catching in order to capture NJ bottom fishing effort. Reports listing capture of bottom fish (defined in Table S6) and a port of departure in NJ were retained. Many more angler trips were reported aboard party vessels, so fishing effort was evaluated separately for party and charter vessels to avoid dominance of fishing effort dynamics by party operators. We first investigated how the for-hire fleet changed during this time period. To do this, we compiled annual counts of reporting vessels, the mean number of anglers per trip, and the mean number of trips per week for party and charter vessels. Next, to build our time series for testing our hypotheses of angler response to regulations, we compiled a weekly time series of fishing effort by summing the total number of angler trips reported by all vessels for each week. This process produced two time series of weekly counts of angler trips on charter and party boats.

Fishing effort can also respond to fishing quality (e.g. Wilson et al. 2020), so we included species-specific catch rates as predictors in our models. Although catch by species is reported in VTRs, reports of catch (number of fish caught) and harvest (number of fish retained, i.e., catch minus fish caught and released) after a trip are prone to recall bias (Bochenek et al., 2012). Catch rates to be used as predictor variables were therefore obtained instead from Marine Recreational Information Program (MRIP) access point intercept survey data (NOAA Fisheries 2021). These surveys take place at ocean access points that are selected within a stratified random sampling regimen. Among other data, respondents report their total species-specific catch, which includes both kept and released fish. Using the procedure described in the MRIP Survey Design and

Statistical Methods documentation (Papacostas and Foster, 2021), we calculated the mean catch per trip for each of our four focal species for each two month survey "wave" in our time series (Fig. S1). Missing values were imputed using linear interpolation for black sea bass and tautog catch rates. Scup catch rates were not included as predictors because of the high number of missing values. Summer flounder missing values occurred in winter months when the stock has migrated off-shore. These missing values were therefore replaced with zero. Average catch rates, rather than spawning stock biomass (SSB), were used to estimate the effects of fishing quality because fish species associated with bottom structure likely exhibit catch rate hyperstability (e.g. Dassow et al. 2019; Erisman et al. 2011). In addition, these catch rates could be calculated for every two months of the time series, while SSB estimates are only available on an annual basis.

NJ fishing regulations for summer flounder, black sea bass, tautog, and scup were collected for the years between 2001 and 2017. Open seasons and possession limits were obtained from annual releases of NJ recreational fishing regulations. Mid-season closures were found by searching the Federal and NJ Registers for rule changes impacting fisheries of the Northeastern United States. State and Federal Registers document rule changes for the federal and NJ state government. The Federal Register can be accessed at https://www.federalregister.gov/ and the NJ Register at https://www.state.nj.us/oal/rules/accessp/. In cases where changes to regulations occurred mid-season, we included only the final regulations in the analysis.

Statistical Analysis

Base ARMA model

We used autoregressive-moving average (ARMA) models to quantify how implementing or changing a management measure affected fishing effort while accounting for autocorrelation and seasonal trends. Fitting a time series model at this granular scale allowed us to detect average effects of changes in regulations within and between years using external regressors. Simultaneously, additional unexplained variation (i.e. variation in angler trips attributable to weather, changes in trip price, etc) is accounted for implicitly by seasonal and ARMA components. ARMA models account for short-term temporal autocorrelation in time series data by fitting autoregressive (AR) terms to lagged observations and moving average (MA) terms to lagged residuals (Box et al. 2008; Box and Jenkins 1970). Weekly time series have a long and non-integer period (52.14 weeks/year), but seasonal models are periodic, being at the same state as one year pervious and repeating. To better align these weekly data with the model's seasonal component, a dynamic harmonic regression approach (Hyndman and Athanasopoulos 2018; Young et al. 1999) was used to fit an appropriate number of Fourier sine-cosine pairs to each time series of fishing effort data. Open seasons for our focal species are highly correlated with seasonality (Fig. 1), so by fitting an identical seasonal trend to each year, we were able to examine how differences in possession limits and season length (e.g. the loss of early and late summer for the summer flounder fishing season) influenced weekly fishing effort in the weeks that did experience differences in regulations among years. Following this approach, increasing numbers of sine-cosine pairs were generated using the forecast package in R v.4.1.0 (Hyndman et al. 2020; R Core Team 2021), and for each of these model fits, the auto.arima function of the forecast package was used to find the best fitting ARMA components. The best fitting combination of ARMA components and Fourier sine-cosine pairs was then chosen based on its AICc score. We tested for serial autocorrelation using the Breusch-Godfrey test.

Candidate model construction

In addition to the aforementioned ARMA and seasonality components, we included as predictors the regulations and catch rate variables relevant to the candidate model's hypothesis

(Table 1, Appendix 1). Considerable variation in catch rates both within and between years were evident (Fig. S1). To indicate possession limits and closed seasons for summer flounder, black sea bass, and tautog, an integer predictor indicated the possession limit in that week. A possession limit of 0 indicated a week where targeting the species was not permitted. Scup possession limits during open season remained at 50 for the entire time series, so an indicator variable was used instead to indicate whether week was open (1) or closed (0) for scup fishing (Table 1). An additional dummy variable ('Something open') was used to indicate whether at least one of the four bottomfish species was available for harvest during the week (i.e. a 0 during a blackout period, 1 otherwise).

The models did not include year as a covariate but instead attempted to explain annual variation in fishing effort through six co-variates that described fishing opportunities in each year. Four continuous variables specified the length of each species' season in days for each year. Two additional continuous variables indicated the total number of blackout days in each year as well as the number of open species available each week. In most years, regulations are announced in late spring of their effective year (i.e. shortly before the start of peak summer season). In 2010, 2011, and 2013, however, season lengths were adjusted mid-season for summer flounder and/or black sea bass. In years when regulations were changed mid-season, the final effective season length was used as a predictor. To correspond with the approximate date of the release of new regulations, annual variables, which included season lengths and annual harvest days, were updated annually on May 1.

The *null model* incorporated the assumption that anglers do not compensate for changes in season length and overlap by changing their behavior. This model therefore included only the focal species' possession limits and their catch rates (Table 1). The other three candidate models included additional predictor variables and interaction effects that tested three hypotheses for how anglers may compensate for regulatory changes (Tables 1 and 2). The *blackout effect model* added the 'Something open' predictor to test the hypothesis that open seasons for any of the four focal species would attract fishing effort, regardless of which species were open. In addition, the annual number of blackout days and its interaction with 'Something open' was included to test for anglers' response to an increasing number of blackout days on the calendar (Table 2). A positive interaction effect would suggest that anglers increased their fishing effort during the remaining open days in response to a higher number of blackout days, and a negative interaction effect would indicate that anglers instead tended to stop fishing in response to these changes. To illustrate, as the number of blackout days in a year increases from 0 to 30, an intensification of fishing effort during the open season would be indicated by a positive parameter value for the two-way interaction of the number of blackout days and the 'Something open' indicator. A week where at least one species is open during a year with 30 blackout days would then have a higher predicted fishing effort than that of a week in a year with 0 blackout days. On a blackout week, however, the 'Something open' indicator is zero, negating the interaction effect.

The *season length model*, in contrast, allowed anglers to display different responses to changes in the season length of different species. The model incorporated this behavior by including season length as a predictor conditional on the corresponding species' open season (i.e. the possession limit is greater than 0). Our hypothesis that anglers would compensate by increasing their fishing effort during the remaining open season would be supported by a negative interaction effect between species-specific season length and the corresponding open season indicator. The *species availability model* accounted for specific substitution patterns used by anglers to maintain their fishing opportunities as the overlap between different species' open seasons was reduced. A negative interaction effect between species-specific open seasons and the number of species that were available would indicate a non-additive response of fishing effort to new open seasons. In other words, adding an additional open species to a given week would result in a lower increase in fishing effort than expected because many of those anglers were already fishing.

Model selection

We evaluated the ability of our four candidate models to explain weekly natural log-transformed total fishing effort for party boats and charter boats. Angler trip counts were log-transformed to account for the greater variance in fishing effort during peak fishing season. The fit of the competing models was compared using the corrected Akaike Information Criterion (AICc) and their associated Akaike weights calculated using the MuMIn package (Bartoń 2020).

To evaluate the relative effects of changes in black sea bass and summer flounder possession limits and season length, we produced annual predictions of angler trips for hypothetical years under different regulations. Tautog regulations were not evaluated in this way because possession limits primarily changed within rather than between years in order to protect tautog from excessive harvest during their summer spawning season (Table S3). For each of these predictions, the fishing effort associated with each week of an average year (i.e. the average value of each week's sine-cosine coefficient pairs across all years of the time series) at average catch rates (i.e. the average value of each week's CPUE for summer flounder, black sea bass, and tautog) were forecast using the best fitting ARMA model with the predict.Arima function (R Core Team, 2021). Only the species of interest was "opened" for the hypothetical forecasted year. A year of weekly predictions were forecasted for each combination of possession limits and season lengths. We then applied a bias correction to these predictions based on a non-parametric smearing adjustment (Duan, 1983), and annual fishing effort was summed for each forecasted year. These predictions produced estimates of the annual fishing effort associated with different combinations of season length and possession limits for specific species. These forecasts are intended to illustrate the relative effects of possession limit and season length changes for different species on angler trips in past years. They are not intended to forecast out-of-sample future changes in fishing effort.

Results

Fleet changes

The NJ for-hire bottom fishing fleet has experienced a number of changes since 2001. The decline in charter vessels reporting each year since 2010 is particularly distinctive, declining from 119 to 57 reporting vessels (Fig. 2A). In spite of the decline in charter vessels, the number of charter boat anglers and the mean number of anglers per charter trip have remained largely constant (Fig. 2B and 2C). This consistency in angler numbers is explained by a near-doubling in the average number of trips taken per charter vessel between 2010 and 2015, from 17.6 to 28.6 charter trips per year. In contrast, the number of party boats has shown a less extreme overall decline, with the exception of a period between 2001 and 2005, where the number of reporting party boats dropped by nearly half (Fig. 2A). This change in party boat numbers corresponds with simultaneous decline in party boat angler trips (Fig. 2B) and a reduction in the average number of trips taken by each vessel (Fig. 2D). Both party boat numbers and angler numbers largely recovered by 2010, but they remained lower than in the early 2000s.

Model selection

Charter boat fishing effort

The time series of charter boat and party boat fishing effort differed in their best fitting models (Tables 3 and 5), indicating that charter and party boat anglers responded differently to changes in regulations. The *blackout effect model* was unambiguously the best fit to charter boat fishing effort, receiving 100% of the Akaike weight (Table 3). The ARMA and seasonal components of the model effectively removed serial autocorrelation of the residuals according to the Breusch-Godfrey test (Table S7). Total fishing effort on charter boats was relatively consistent between years (Fig. 2B), and variation in weekly effort was driven mainly by seasonality rather than by open seasons of specific species (Tables 4 and S8). In spite of these species' popularity, neither black sea bass, summer flounder, or tautog possession limits, nor scup open seasons were associated with significant changes in fishing effort on their own (Table 4). All else being equal, the opening of at least one of the four species was associated with an over 6-fold increase in angler trips (i.e. exp(1.954)=7.06), suggesting that charter anglers are flexible in their species preferences (p=0.008, Table 4). All else being equal, the availability of at least one of the four focal species was associated with an over 600% increase in fishing effort compared to a "blackout" day. The interaction of the 'Something open' indicator with the annual number of blackout days, however, was not significant (p=0.143, Table 4). Charter boat anglers therefore did not appear to leave the fishery in response to increasing numbers of blackout days, which would have been evident by a negative interaction. Nor did they appear to compensate for blackout days by increasing fishing effort, which would have been evident by a positive interaction. Fishing effort of charter angler trips also did not appear to respond to summer flounder, black sea bass, or tautog catch rates when aggregated at the two-month level.

Party boat fishing effort

The species availability model was unambiguously the best fit to the time series of party boat angler trips (Table 5). Summer flounder, tautog, and black sea bass possession limits were significant predictors of fishing effort, where an increase in limit of 1 fish was respectively associated with a 26%, 15%, and 5% increase in angler trips. The opening of multiple species simultaneously, however, did not have an additive effect on fishing trips. The negative interaction between summer flounder, tautog, and black sea bass open seasons and the number of open species suggests that a subset of the anglers fishing for summer flounder, for example, were already previously fishing for black sea bass or tautog before the flounder season opened. Weeks where all three species are open for harvest therefore experienced fewer angler trips than would be predicted by only the species-specific possession limits. Scup open seasons, in contrast, were associated with increased angler trips in combination with the availability of additional target species. In our dataset, scup only occurred in combination with at least one other species (N species=2). During these combined seasons of two species (usually tautog and scup), scup is associated with only a small decrease in mean angler trips (i.e. $\exp(-0.944+1*0.99)=0.996$, or a 0.4% decrease in angler trips). In combination with two or three other species, however, scup season is respectively associated with a 63% or 268% increase in fishing trips. These overlaps typically occurred in the peak summer season, when scup is available inshore. During the rest of its winter open season, scup has migrated offshore to deeper water, where it is more difficult to target (NMFS 1999). Fishing effort did not obviously respond to black sea bass or summer flounder catch rates, but angler trips did increase by 3% in correspondence with an increase in tautog catch rates of 1 fish per trip ($p = 0.015$, Table 6).

Multicollinearity was detected between certain predictor variables for the species availability model, with variance inflation factors (VIF) as high as 9.9 (Table S11). To test the sensitivity of the parameter estimates to this collinearity, we completed a supplemental analysis by re-fitting the model without the most highly correlated predictors (i.e. summer flounder possession limits and catch rates). Coefficient estimates were effectively the same, except for the interaction effect of tautog possession limits with the number of open species (Tables S12 and S13). When summer flounder-associated predictors were removed from the model, this interaction was no longer significant.

Black sea bass seasons experienced substantial variation in both possession limits and season lengths among years (Fig. 3). Only modest increases in annual angler trips relative to closed season were associated with the possession limits of two or three fish that were implemented in peak summer fishing seasons starting in 2014 (Fig. 1). Higher possession limits, in contrast, were associated with tens of thousands more angler trips per year. Summer flounder season lengths experienced less change among years in our analysis (Fig. 4A). In spite of this limited variation of season lengths, distinct changes in annual fishing effort were detected. As possession limits were lowered, however, the response of annual fishing effort to season length became less distinct (Fig 4B).

Discussion

Previous survey-based studies of recreational anglers' stated preferences have highlighted the importance of preserving fishing opportunities in the form of open fishing seasons in order to maintain angler satisfaction (Brinson and Wallmo 2017; Young et al. 2019). The use of VTR data allowed us to investigate the empirical response of anglers aboard for-hire vessels to reduced fishing opportunity. We found evidence of substantial reductions in annual fishing effort within the party and charter boat fisheries as a result of reduced possession limits and, to a lesser extent, contracting season lengths. These results support the concerns expressed by focus group participants regarding reduced profitability of for-hire fishing vessels in the face of these increased restrictions. Fishing effort dynamics within the charter boat fishery were best explained by the *blackout effect model*, where the ability to harvest any one of the four species was a more important predictor of fishing effort than the availability of any specific species. Fishing effort in the party boat fishery, in contrast, was best explained by the *species availability model,* and angler trips specifically responded positively to summer flounder and black sea bass open seasons. The non-additive effects of additional open seasons suggested a significant degree of substitution behavior occurring among party boat angler trips as species open and close throughout the season. The interaction effect of tautog open season with species availability was non-significant in the sensitivity model fit that eliminated summer flounder predictors. Substitution behavior may therefore be less common among tautog anglers. Among charter boat anglers, however, substitution behavior appears to be even more prevalent, as indicated by the strong positive effect of the "Something open" predictor.

Although substitution behavior appears to vary between charter and party boat anglers, our ability to infer specific angler behaviors is limited because the number of angler trips in a week also depends on the availability of trips for hire. Responses of angler trips to regulations may therefore indicate differences in operator behavior rather than angler preferences. The corresponding decline in federally permitted charter vessels and increase in annual trips per vessel, for example, suggest that the demand for charter trips may exceed the supply. If the remaining operators are allowed to target bottom fish on a given day, they will most likely be able to reserve enough customers to fill their vessel. The response of charter angler trips to the availability of "something" may therefore be an indication of operator behaviors. Angler trips aboard party vessels, however, appeared to show more room for variation. Similar to charter trips, the number of weekly party angler trips can be limited by the availability of spots aboard party vessels. Conversely, at very low demand, party vessels will cancel trips if the number of spots sold do not recoup costs. However, considerably more variation is possible in the number of anglers aboard large party boats once this threshold of profitability is reached, suggesting to us that party boat fishing effort dynamics primarily reflect angler preferences. In particular, the large negative effects of reduced possession limits on the number of weekly angler trips suggest that many anglers have quit bottom fishing on party vessels in response to these changes. Because substitution behaviors do not appear to be as strong in the party fishery as in the charter sector, party vessel operators probably could not rely on angler substitution of less popular bottom species to maintain their profits. Party vessel operators may therefore be particularly vulnerable to the negative economic effects of increased restrictions on bottomfish harvest.

Considerable additional variation existed in angler trips that was not explained by changes in regulations. For example, a nearly 50% drop in angler trips occurred between 2005 and 2010 (Fig. 5), which did not correspond to any specific changes in regulations. This time period does, however, roughly correspond with a period of conflict over reductions in the acceptable biological catch (ABC) for summer flounder, the implementation of conservation equivalency among states, and the stock assessment methods used by fisheries scientists (Terceiro 2011). The rebound in party boat angler numbers in 2010 is also coincident with a new stock assessment indicating that the summer flounder stock was not overfished and did not experience overfishing between 2008 and 2010 (Terceiro 2018). As a new control rule was implemented after the 2011 season, however, the ABC was reduced, leading to another round of conflict between scientists, managers, and stakeholders (Terceiro 2018). At the seasonal level, these changes in annual fishing effort stem from a reduction in “peak” fishing effort for summer flounder during the summer months of May through August (Fig. 5A). Although black sea bass availability is also associated with higher fishing effort aboard party boats, similar patterns in monthly fishing effort are evident during years with and without year-round black sea bass seasons (Fig. 5B). Therefore, although fishing regulations influenced the number of angler trips each week, we speculate that trust in management and public perceptions of summer flounder stock health are potentially important predictors of fishing effort.

Vessel Trip Report data represent a large and mostly untapped resource for studying marine recreational fishing effort dynamics. However, they also present several challenges. First, only vessels with federal permits are required to submit VTRs. Federal permit are required for summer flounder, black sea bass, and scup fishers, but not for tautog. Charter vessels in particular may be underreported in the VTR data if they do not target either of these three species. In addition, VTRs report catch but not target species. We therefore defined bottomfishing trips based on the reported capture of at least one of nine bottom-associated species, which may have excluded some bottomfishing trips where nothing was caught. However, fishing trips with no reported catch made up only 1.5% of all fishing reports, so we believe that any effects of their elimination should be minimal. By filtering data by catch, we may also have included some trips targeting non-bottomfish species, such as striped bass (*Morone saxttilis*) or bluefish (*Pomatomus saltatrix*), during which bottomfish were caught incidentally. Both of these species remained open during the "blackout" periods recorded in our time series. The distinctively reduced weekly effort aboard charter vessels evident during these blackout periods suggests, however, that our filtering was largely successful at removing these trips. In addition, minimum length limits are important issues for fishery stakeholders (Table S5), but they were not included as predictor variables because of excessive collinearity with possession limits. Minimum length limits tended to increase as possession limits decreased, so some of the effects of minimum length limits on fishing effort were explained in our model fits by changes in possession limits. Lastly, although VTRs provide a census count of anglers aboard federally permitted for-hire vessels, operators targeting tautog are not required to acquire a federal permit. We expected that operators targeting tautog would also target other highly popular bottomfish that do require federal permits, but we may have missed vessels specializing in tautog fishing, particularly among charter vessels.

The apparent willingness of anglers to substitute target species aboard charter boats, and to a lesser extent aboard party boats, has a number of implications for management of marine recreational fisheries. In particular, the relatively stable fishing effort in the charter sector regardless of individual species' closures suggests that discards may be high for closed species that are caught incidentally when anglers target other bottom fish. In other fisheries where anglers show high willingness to substitute target species, discard mortality has been demonstrated to reduce the effectiveness of seasonal closures (Chagaris et al., 2019). This phenomenon highlights the importance of understanding angler motivations for maintaining fishing opportunities and/or harvest. The relative importance of preserving fishing opportunity versus harvest capacity has been investigated in a variety of systems (e.g. Melnychuk et al., 2021; Young et al., 2019) and angler response to these changes appears to depend in part on anglers' willingness to re-allocate fishing effort to other time periods or alternative species. In other harvest-oriented fisheries, anglers express strong preferences for higher possession limits (e.g. Mackay et al. 2020). Reductions in possession limits and complete closures reduce anglers' harvest capacity and therefore their expected satisfaction, resulting in reduced fishing effort overall if anglers are unwilling to substitute less-restricted species (Powell et al., 2010).

Redirected fishing effort can lead to increased harvest of substitute species (Beaudreau et al., 2018) or increased discard mortality when closed or restricted species are caught and released (Chagaris et al., 2019). Although we investigated only the response of for-hire recreational fishing effort, the effect of regulation change on total recreational fishing effort also depends on the response of private boat anglers. These anglers do not rely on the availability of spots aboard for-hire vessels, suggesting that they have more ability to respond to closures by re-allocating fishing effort to different times of year. This response was observed in the Gulf of Mexico red snapper fishery when season length was drastically reduced (Chagaris et al., 2019; Powers and Anson, 2018, 2016). In less extreme instances of season reductions, however, private anglers may instead target alternative species to maintain their level of harvest or opportunities to fish, leading to a more stable pattern of fishing effort similar to our observations of charter vessels. Alternatively, the costs of maintaining a private vessel may drive some private anglers to leave the fishery when regulations become more stringent. If this choice is widespread, fishing effort, harvest, and discards would decline, but coastal communities would also experience the negative economic impacts associated with reduced angler participation. Responses to regulations among both private and for-hire anglers are therefore important to understand when evaluating the effects of new regulations on fishing effort, harvest, and discard mortality. An ongoing project by this team is using stated preference methods to investigate these potential responses among private and for-hire anglers.

Fisheries managers constantly consider tradeoffs in ecological, social, and economic objectives with the goal of maintaining stocks above safe harvest limits, maintaining public access to the fishery, and supporting the economies of coastal communities (e.g. Punt 2017). In addition to wrestling with uncertainties in population dynamics of important stocks, considerable uncertainty surrounds the response of fishers to changes in regulations and ecological conditions (Fulton et al. 2011). Accounting for the responses of human stakeholders with heterogeneous and often competing preferences is vital for enacting proactive management decisions (Johnston et al. 2010). For-hire vessels make up one of these heterogeneous stakeholder groups and provide relatively low-cost access to fish stocks for recreational anglers globally. Recreational fisheries are also a major source of fishing mortality (Coleman et al. 2004; Cooke and Cowx 2004), and many of the costs of reduced harvest are borne by for-hire vessels, their customers, and the coastal communities relying on their economic contributions. In recent years, for example, fleet diversity of the recreational fishery in the Mid-Atlantic has declined as more anglers switch to shore-based modes of fishing and away from for-hire vessels (NEFSC 2021). Between uncertainty surrounding new regulations each year and reduced participation of anglers in the for-hire sector, for-hire operators are left in a precarious economic position. Illustrating this concern, one focus group participant stated, “Name me one industry besides fishing […] where we can’t go year to year and we can’t budget, we can’t forecast, we can’t predict. And you show me one industry where you have that every year, year after year, and still stay in business.” Fisheries managers are therefore left in the difficult position of being accountable for keeping recreational harvest within imposed limits while also balancing the biological, social, and economic objectives of stakeholders, including these for-hire operators. Uncertainty associated with angler responses to changes in fishing regulations is an important limitation in managers’ ability to constrain recreational harvest. Further investigations of angler behavioral responses to regulation should continue to help managers to enact regulations that prevent overharvest while meeting the economic needs of coastal communities.

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Tables

Table 1: Predictor variable descriptions for each of the four models. Checks mark the predictors that were included in each model, and asterisks indicate the predictors that were included as predictors conditional on the corresponding open season. Obelisks indicate predictors with two-way interactions with corresponding species' possession limits. Species-specific regulations and catch rates are indicated by the following abbreviations: black sea bass (BSB), summer flounder (SMF), tautog (TOG), and scup (SCP).

Predictors	Description	Variable type	Update frequency	Null model	Blackout effect model	Season length model	Species availability model
'BSB PL' 'SMF PL' 'TOG PL' 'SCP open'	Possession limits of each focal species, with 0 indicating closed season. Scup possession limits did not change, so scup open season is a binary variable, with 1 indicating open season and 0 closed.	Integer	Weekly	✓	✓	✓	✓
'CPUE BSB' 'CPUE SMF' 'CPUE TOG'	Mean catch per trip of each focal species	Continuous	Bimonthly	✓	✓	✓	✓
'Something open'	Indicator that at least one of the focal species' seasons is open (i.e. PL > 0)	Binary	Weekly		✓		
'N blackout days'	Annual number of blackout days, where none of the focal species are open	Integer	Annual		✓		

‘Season length BSB’ ‘Season length SMF’ ‘Season length TOG’ ‘Season length SCP’	Number of days of open season per year for each focal species	Integer	Annual	✓*	
‘N species open’	Number of focal species open each week	Integer	Weekly		✓†

Table 2: Hypotheses about angler behavioral responses to changes in regulations for flounder (SMF), black sea bass (BSB), tautog (TOG), and scup (SCP). Hypotheses are illustrated with representative quotations from stakeholder focus groups and operationalized in candidate models with different interaction effects. Species-specific regulations and catch rates are indicated by the following abbreviations: black sea bass (BSB), summer flounder (SMF), tautog (TOG), and scup (SCP). Bolding indicates the interaction sign that supports the hypothesis represented by the selected quotation. Further detail on model parameterization can be found in Appendix 1 of the Supplementary materials.

Model	Representative quotation	Interaction effects	Interpretation
0. Null	N/A	N/A	N/A
1. Blackout effects	*"We do see a tremendous setback that occurs because of the eight or ten-day closure during the end of June. The people just kind of stop coming when that happens and you go* [snaps fingers] *it's over."*	Something open * number of blackout days	Positive: Anglers compensate for fewer harvest days (or more blackout days) with higher weekly fishing effort **Negative: Anglers leave the fishery on year with fewer harvest days/more blackout days.**
2. Season length	*"We used to fish through March. When you could do that, you didn't need to all press in to whatever the next fishery was…Now everybody's just trying to get every last day in that they can because there's so few of them available."*	Season length BSB : BSB open Season length SMF : SMF open Season length TOG : TOG open Season length SCP : SCP open	**Negative: Effort compression. Anglers compensate for shorter seasons of particular species by increasing weekly fishing effort while that species is open.**

1. Species availability	*"[Black] sea bass is the only thing open. [Tau]tog's closed, fluke's closed. All of the angler pressure is now on sea bass. Where it used to spread out and diversify and the anglers would do other things, no matter what it was. You have a very severe angler impact on a single species due to the way regulations are set up, leaving no other choice but to target specific species."*	BSB PL * N species open SMF PL * N species open TOG PL * N species open SCP Open * N species open	**Negative: Anglers switch target species when the season for their initial target species closes.**

Table 3: Model fit and Akaike weights of all candidate models for the time series of charter boat fishing effort. Bolded values indicate the lowest AICc and highest weight.

Model	AICc	AICc weight	Log Likelihood	# Parameters
Null model	2192.76	0	-1052.24	42
Blackout effect model	**2173.31**	**1**	**-1063.02**	**23**
Season length model	2189.84	0	-1044.11	48
Species availability model	2193.47	0	-1048.16	46

Table 4: Coefficients of blackout effect model fit to charter boat fishing effort time series. Coefficients of the autoregressive, moving average, and seasonal component can be found in Table S8. Species-specific regulations and catch rates are indicated by the following abbreviations: black sea bass (BSB), summer flounder (SMF), tautog (TOG), and scup (SCP). Bolded values are significant at the p<0.05 level. DF=870

Coefficient	Estimate	Standard error	T value	P value
Intercept	**2.203**	**0.760**	**2.897**	**0.004**
BSB PL	0.004	0.005	0.733	0.464
SMF PL	0.018	0.022	0.852	0.394
TOG PL	0.032	0.025	1.307	0.192
SCP Open	0.229	0.152	1.507	0.132
Something open	**1.954**	**0.740**	**2.641**	**0.008**
N blackout days	0.024	0.017	1.465	0.143
Something open * N blackout days	-0.019	0.017	-1.170	0.242
SMF CPUE	0.010	0.029	0.350	0.727
BSB CPUE	0.007	0.006	1.069	0.285
TOG CPUE	-0.017	0.019	-0.902	0.367

Table 5: Model fit and Akaike weights of all candidate models for the time series of party boat fishing effort. Bolded values indicate the lowest AICc and highest weight.

Model	AICc	AICc weight	Log Likelihood	# Parameters
Null model	1517.43	0	-726.55	31
Blackout effect model	1502.68	0	-715.94	34
Season length model	1510.27	0	-710.29	39
Species availability model	**1482.59**	**1**	**-704.82**	**35**

Table 6: Coefficients of species availability model fit to party boat fishing effort time series. Coefficients of the autoregressive, moving average, and seasonal component can be found in Table S10. Species-specific regulations and catch rates are indicated by the following abbreviations: black sea bass (BSB), summer flounder (SMF), tautog (TOG), and scup (SCP). Bolded values are significant at the $p<0.05$ level. DF=855

Coefficient	Estimate	Standard error	T value	P value
Intercept	**5.745**	**0.168**	**34.228**	**<0.0001**
BSB PL	**0.050**	**0.010**	**5.050**	**<0.0001**
SMF PL	**0.227**	**0.045**	**5.089**	**<0.0001**
TOG PL	**0.141**	**0.033**	**4.283**	**<0.0001**
SCP Open	**-0.994**	**0.268**	**-3.712**	**0.0002**
BSB PL x N species available	**-0.014**	**0.004**	**-3.880**	**0.0001**
SMF PL x N species available	**-0.047**	**0.014**	**-3.474**	**0.001**
TOG PL x N species available	**-0.034**	**0.013**	**-2.506**	**0.012**
SCP Open x N species available	**0.495**	**0.095**	**5.185**	**<0.0001**
SMF CPUE	0.005	0.023	0.219	0.827
BSB CPUE	0.004	0.004	0.923	0.356
TOG CPUE	**0.030**	**0.012**	**2.444**	**0.015**

Figures

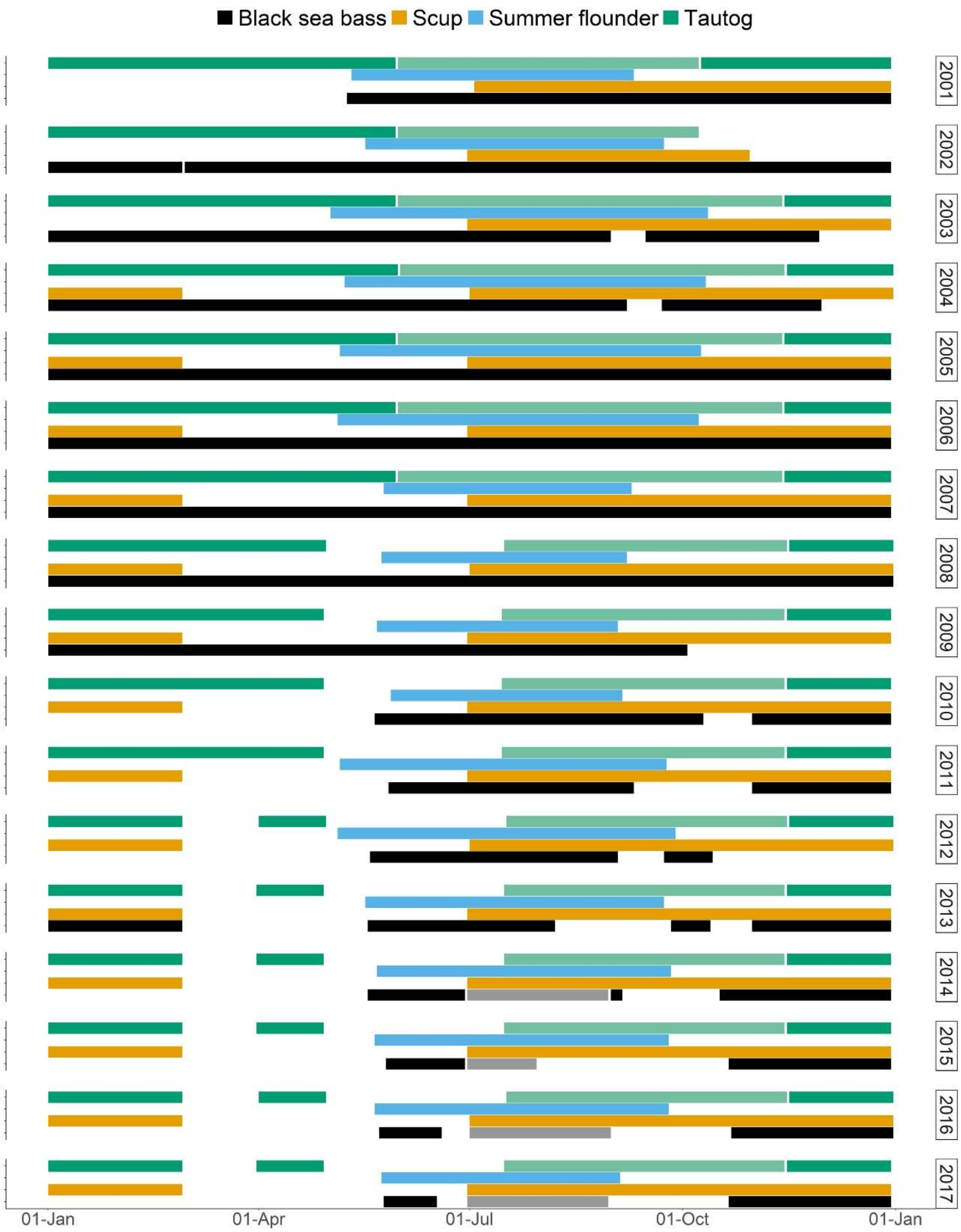

Figure 1: Changes in New Jersey season length and overlap for tautog (top, green), summer flounder(blue), scup (yellow), and black sea bass (bottom, black) between 2001 and 2017. Colored bars delineate open seasons for each of the four species. Light green bars for tautog

indicate 1 fish possession limits during the summer and fall months. Gray bars starting in 2014 illustrate black sea bass summer seasons with 2 or 3 fish possession limits.

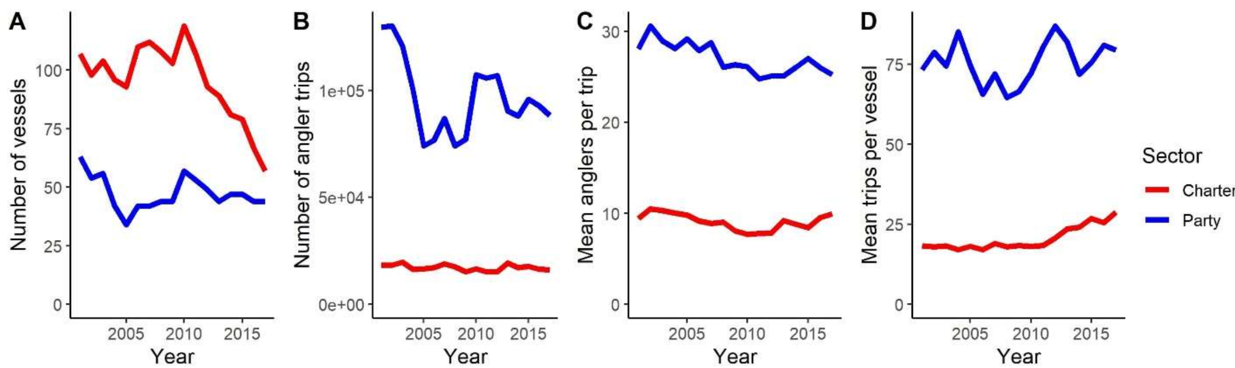

Figure 2: Changes in the annual number of vessels reporting from the for-hire bottom-fishing fleet (A), the number of angler trips reported (B), the mean number of anglers per trip reported (C), and the mean number of trips per vessel reported (D) between 2001 and 2017 in the NJ charter and party boat fleets.

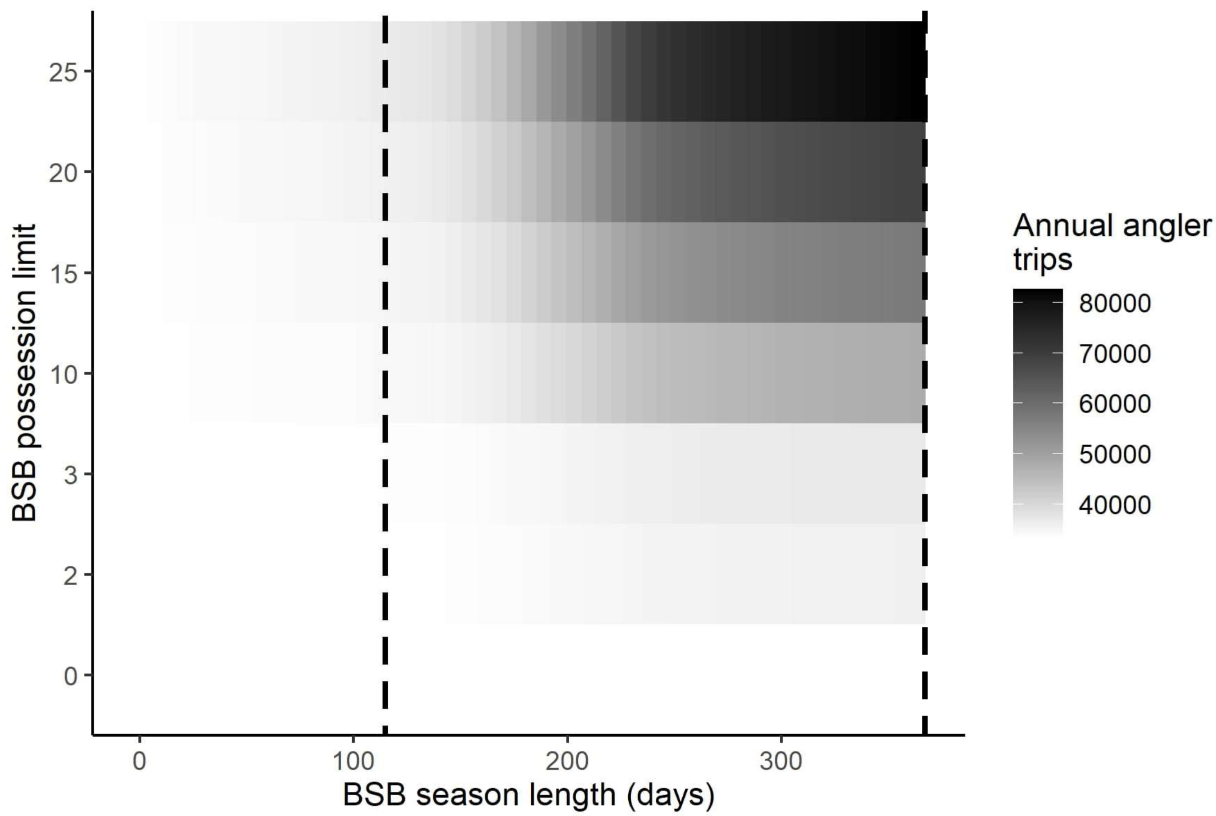

Figure 3: Annual party boat angler trips predicted across a range of season lengths and possession limits for black sea bass. In these model predictions forecasting effort from hypothetical regulations, only black sea bass season is open. The area between the two dashed lines indicates season lengths that are represented in the data.

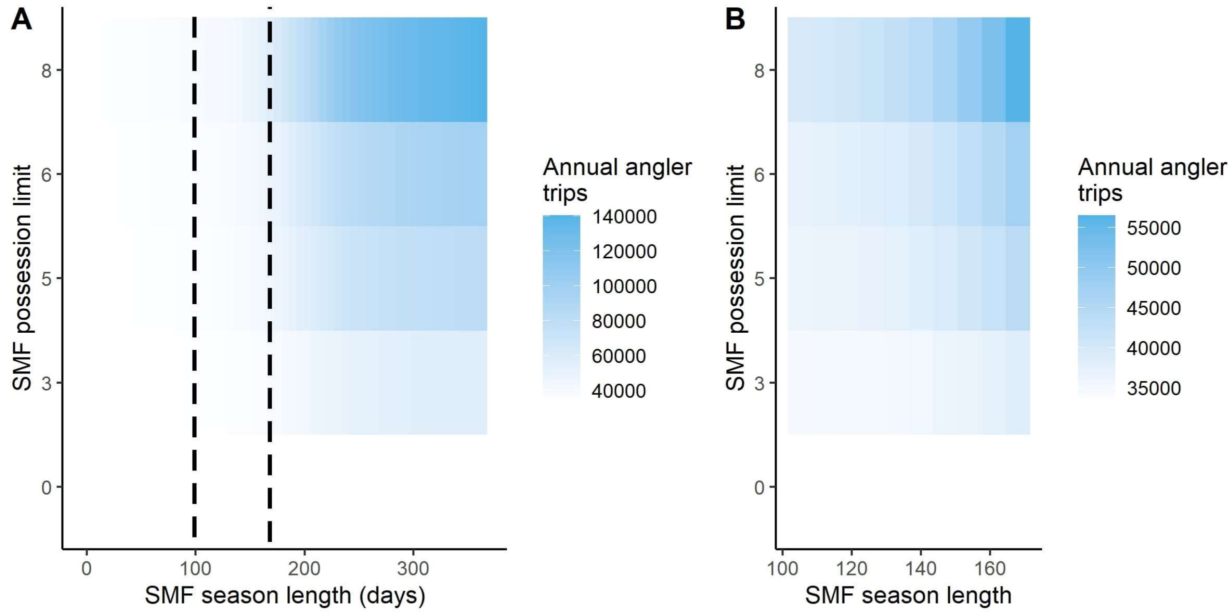

Figure 4: Annual party boat angler trips predicted across a full range of possession limits, hypothetical season lengths (A), and the season lengths represented in the data (B) for summer flounder (i.e. B is a subset of A). The area between the two dashed lines indicates season lengths that are represented in the data. In these model predictions forecasting effort from hypothetical regulations, only summer flounder season is open.

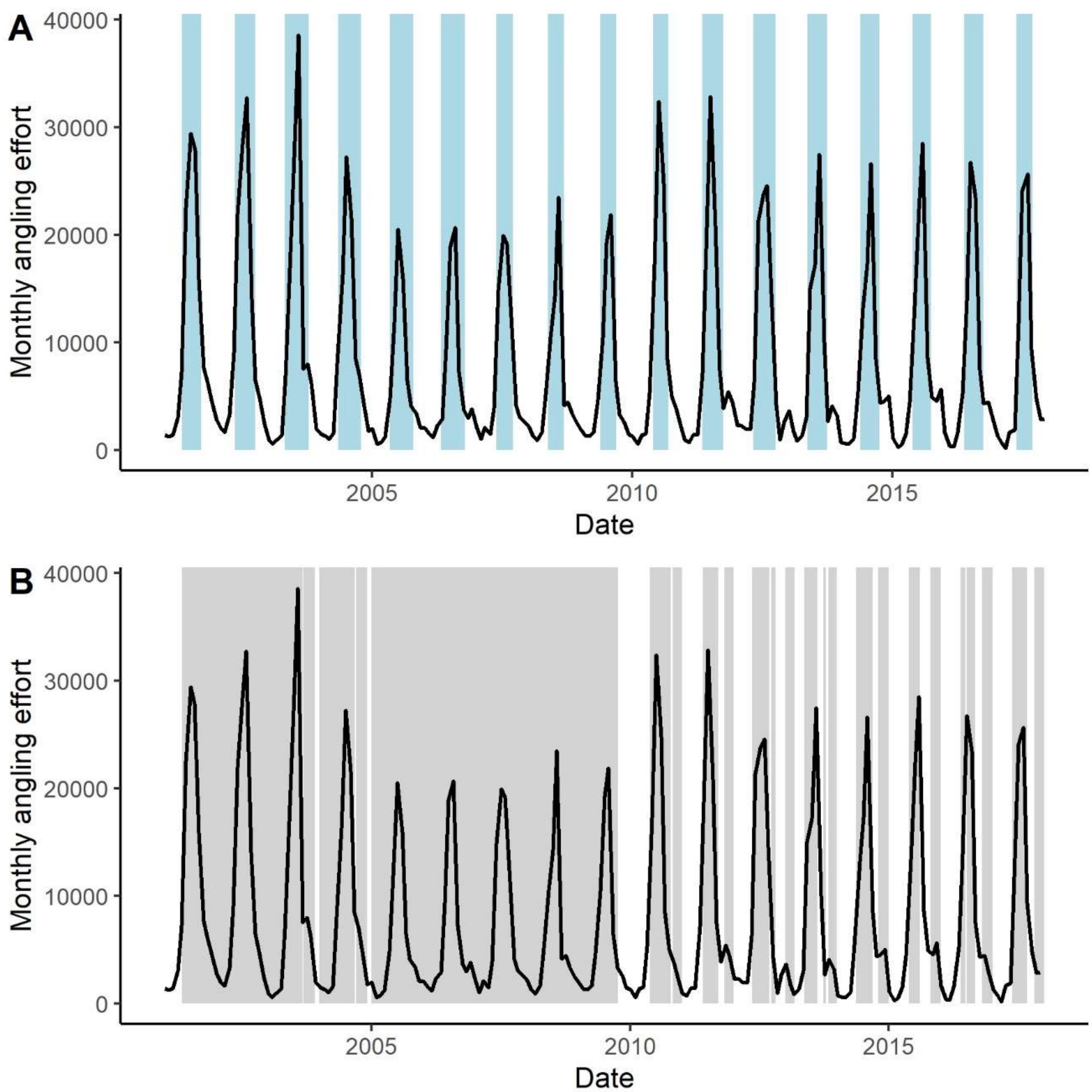

Figure 5: Monthly fishing effort in the party boat sector of the NJ for-hire recreational fishery. Summer flounder open seasons are highlighted in blue on plot A, and black sea bass seasons are in gray on plot B.

Appendix

Candidate models take the following form for the best fit number of sine-cosine pairs, k, autoregressive coefficients p, and moving average coefficients q at time t. Sine-cosine pairs are fit to observations at time t through the ω coefficients. Error terms are indicated by ε. Catch per unit effort (CPUE) and regulation covariates are included for black sea bass (BSB), summer flounder (SMF), tautog (TOG), and scup (SCP).

Null model

$$
\begin{aligned}
&Ln(1 + N\ angler\ trips_t) \\
&\quad = \sum_{k=1}^{K} \left[\alpha_{1,k} \cos(\omega_{1k} t) + \alpha_{2,k} \sin(\omega_{2k} t)\right] \\
&\quad + \sum_{p=1}^{P} \phi_p \ln(N\ anglers)_{t-p} \\
&\quad + \sum_{q=1}^{Q} \theta_q \varepsilon_{t-q} \\
&\quad + \beta_0 + \beta_1\ Possession\ limit\ SMF_t + \beta_2 Possession\ limit\ BSB_t \\
&\quad + \beta_3 TOG\ Possession\ limit_t + \beta_4 Open\ season\ SCP_t + \beta_5 CPUE\ SMF_t \\
&\quad + \beta_6\ CPUE\ BSB_t + \beta_7 CPUE\ TOG_t + \varepsilon_t
\end{aligned}
$$

$$\varepsilon_t \sim N(0, \sigma^2)$$

Blackout effect model

$$
\begin{aligned}
&Ln(1 + N\ angler\ trips_t) \\
&= \sum_{k=1}^{K}\left[\alpha_{1,k}\cos(\omega_k t) + \ \alpha_{2,k}\sin\left(\omega_k t\right)\right] \\
&+ \sum_{p=1}^{P}\phi_p \ln(N\ anglers)_{t-p} \\
&+ \sum_{q=1}^{Q}\theta_q \varepsilon_{t-q} \\
&+ \beta_0 + \beta_1 Possession\ limit\ SMF_t + \beta_2 Possession\ limit\ BSB_t \\
&+ \beta_3 Possession\ limit\ TOG_t + \beta_4 Open\ season\ SCP_t + \beta_5 CPUE\ SMF_t \\
&+ \beta_6\ CPUE\ BSB_t + \beta_7 CPUE\ TOG_t + \beta_8\ Something\ open_t \\
&+ \beta_9\ N\ blackout\ days_t + \beta_{10}\ Something\ open_t\ * N\ blackout\ days_t + \ \varepsilon_t
\end{aligned}
$$

$$\varepsilon_t \sim N(0, \sigma^2)$$

Season length model

$$
\begin{aligned}
&Ln(1 + N\ angler\ trips_t) \\
&\quad = \sum_{k=1}^{K} \left[\alpha_{1,k} \cos(\omega_k t) + \alpha_{2,k} \sin(\omega_k t)\right] \\
&\quad + \sum_{p=1}^{P} \phi_p \ln(N\ anglers)_{t-p} \\
&\quad + \sum_{q=1}^{Q} \theta_q \varepsilon_{t-q} \\
&\quad + \beta_0 + \beta_1 Possession\ limit\ SMF_t + \beta_2 Possession\ limit\ BSB_t \\
&\quad + \beta_3 Possession\ limit\ TOG_t + \beta_4 Open\ season\ SCP_t + \beta_5 CPUE\ SMF_t \\
&\quad + \beta_6\ CPUE\ BSB_t + \beta_7 CPUE\ TOG_t + \beta_8\ Season\ length\ SMF_t \\
&\quad + \beta_9\ Season\ length\ BSB_t + \beta_{10} Season\ length\ TOG_t \\
&\quad + \beta_{11}\ Season\ length\ SCP_t + \beta_{12}\ Open\ season\ SMF_t * Season\ length\ SMF_t \\
&\quad + \beta_{13} Open\ season\ BSB_t * Season\ length\ BSB_t \\
&\quad + \beta_{14} Open\ season\ TOG_t * Season\ length\ TOG_t \\
&\quad + \beta_{15}\ Open\ season\ SCP_t * Season\ length\ SCP_t + \varepsilon_t
\end{aligned}
$$

$$\varepsilon_t \sim N(0, \sigma^2)$$

Species availability model

$$Ln(1 + N\ angler\ trips_t)$$

$$= \sum_{k=1}^{K} [\alpha_{1,k} \cos(\omega_k t) + \alpha_{2,k} \sin(\omega_k t)]$$

$$+ \sum_{p=1}^{P} \phi_p \ln(N\ anglers)_{t-p}$$

$$+ \sum_{q=1}^{Q} \theta_q \varepsilon_{t-q}$$

$$+ \beta_0 + \beta_1 Possession\ limit\ SMF_t + \beta_2 Possession\ limit\ BSB_t$$

$$+ \beta_3 Possession\ limit\ TOG_t + \beta_4 Open\ season\ SCP_t + \beta_5 CPUE\ SMF_t$$

$$+ \beta_6\ CPUE\ BSB_t + \beta_7 CPUE\ TOG_t$$

$$+ \beta_8 Possession\ limit\ SMF_t * N\ species\ open_t$$

$$+ \beta_9\ Possession\ limit\ BSB_t * N\ species\ open_t$$

$$+ \beta_{10}\ Possession\ limit\ TOG_t * N\ species\ open_t$$

$$+ \beta_{11}\ Open\ season\ SCP_t * N\ species\ open_t + \varepsilon_t$$

$$\varepsilon_t \sim N(0, \sigma^2)$$

Supplementary materials

Table S1: Black sea bass seasons, possession limits, and minimum length limits from 2001 to 2017.

Season open	Season close	Possession limit	Minimum length limit (inches)
5/10/2001	12/31/2001	25	11
1/1/2002	2/28/2002	25	11
3/1/2002	12/31/2002	25	11.5
1/1/2003	9/1/2003	25	12
9/16/2003	11/30/2003	25	12
1/1/2004	9/7/2004	25	12
9/22/2004	11/30/2004	25	12
1/1/2005	12/31/2005	25	12
1/1/2006	12/31/2006	25	12
1/1/2007	12/31/2007	25	12
1/1/2008	12/31/2008	25	12
1/1/2009	10/4/2009	25	12.5
5/22/2010	10/11/2010	25	12.5
11/1/2010	12/31/2010	25	12.5
5/28/2011	9/11/2011	25	12.5
11/1/2011	12/31/2011	25	12.5
5/19/2012	9/3/2012	25	12.5
9/23/2012	10/14/2012	25	12.5
1/1/2013	2/28/2013	15	12.5
5/19/2013	8/8/2013	20	12.5
9/27/2013	10/14/2013	20	12.5
11/1/2013	12/31/2013	20	12.5
5/19/2014	6/30/2014	15	12.5
7/1/2014	8/31/2014	3	12.5
9/1/2014	9/6/2014	15	12.5
10/18/2014	12/31/2014	15	12.5
5/27/2015	6/30/2015	15	12.5
7/1/2015	7/31/2015	2	12.5
10/22/2015	12/31/2015	15	12.5
5/23/2016	6/19/2016	10	12.5
7/1/2016	8/31/2016	2	12.5
10/22/2016	12/31/2016	15	13
5/26/2017	6/18/2017	10	12.5
7/1/2017	8/31/2017	2	12.5
10/22/2017	12/31/2017	15	12.5

Table S2: Season lengths, possession limits, and minimum length limits for summer flounder between 2001 and 2017. Differences in regulations between marine and Delaware Bay regulations were implemented starting in 2016.

Season open	Season close	Possession limit marine	Possession limit Del. Bay and tributaries	Minimum length limit marine (inches)	Minimum length limit Del. Bay and tributaries (inches)
5/15/1999	10/11/1999	8	8	15.5	15.5
5/6/2000	10/20/2000	8	8	15.5	15.5
5/12/2001	9/11/2001	8	8	16	16
5/18/2002	9/24/2002	8	8	16.5	16.5
5/3/2003	10/13/2003	8	8	16.5	16.5
5/8/2004	10/11/2004	8	8	16.5	16.5
5/7/2005	10/10/2005	8	8	16.5	16.5
5/6/2006	10/9/2006	8	8	16.5	16.5
5/26/2007	9/10/2007	8	8	17	17
5/24/2008	9/7/2008	8	8	18	18
5/23/2009	9/4/2009	6	6	18	18
5/29/2010	9/6/2010	6	6	18	18
5/7/2011	9/25/2011	8	8	18	18
5/5/2012	9/28/2012	5	5	17.5	17.5
5/18/2013	9/24/2013	5	5	17.5	17.5
5/23/2014	9/27/2014	5	5	18	18
5/22/2015	9/26/2015	5	5	18	18
5/21/2016	9/25/2016	5	4	18	17
5/25/2017	9/5/2017	3	3	18	17

Table S3: Season lengths, possession limits, and minimum length limits for tautog between 2001 and 2017.

Season open	Season close	Possession limit	Minimum length limit (inches)
1/1/2001	5/31/2001	10	14
6/1/2001	10/9/2001	1	14
10/10/2001	12/31/2001	10	14
1/1/2002	5/31/2002	10	14
6/1/2002	10/9/2002	1	14
1/1/2003	5/31/2003	4	14
6/1/2003	11/14/2003	1	14
11/15/2003	12/31/2003	8	14
1/1/2004	5/31/2004	4	14
6/1/2004	11/14/2004	1	14
11/15/2004	12/31/2004	8	14
1/1/2005	5/31/2005	4	14
6/1/2005	11/14/2005	1	14
11/15/2005	12/31/2005	6	14
1/1/2006	5/31/2006	4	14
6/1/2006	11/14/2006	1	14
11/15/2006	12/31/2006	8	14
1/1/2007	5/31/2007	4	14
6/1/2007	11/14/2007	1	14
11/15/2007	12/31/2007	8	14
1/1/2008	4/30/2008	4	14
7/16/2008	11/15/2008	1	14
11/16/2008	12/31/2008	6	14
1/1/2009	4/30/2009	4	14
7/16/2009	11/15/2009	1	14
11/16/2009	12/31/2009	6	14
1/1/2010	4/30/2010	4	14
7/16/2010	11/15/2010	1	14
11/16/2010	12/31/2010	6	13
1/1/2011	4/30/2011	4	14
7/16/2011	11/15/2011	1	14
11/16/2011	12/31/2011	6	14
1/1/2012	2/28/2012	4	15
4/1/2012	4/30/2012	4	15
7/17/2012	11/15/2012	1	15
11/16/2012	12/31/2012	6	15
1/1/2013	2/28/2013	4	15
4/1/2013	4/30/2013	4	15
7/17/2013	11/15/2013	1	15

11/16/2013	12/31/2013	6	15
1/1/2014	2/28/2014	4	15
4/1/2014	4/30/2014	4	15
7/17/2014	11/15/2014	1	15
11/16/2014	12/31/2014	6	15
1/1/2015	2/28/2015	4	15
4/1/2015	4/30/2015	4	15
7/17/2015	11/15/2015	1	15
11/16/2015	12/31/2015	6	15
1/1/2016	2/28/2016	4	15
4/1/2016	4/30/2016	4	15
7/17/2016	11/15/2016	1	15
11/16/2016	12/31/2016	6	15
1/1/2017	2/28/2017	4	15
4/1/2017	4/30/2017	4	15
7/17/2017	11/15/2017	1	15
11/16/2017	12/31/2017	6	15

Table S4: Season lengths, minimum length limits, and possession limits for scup between 2001 and 2017.

Season open	Season close	Possession limit	Minimum length limit (inches)
7/4/2001	12/31/2001	50	9
7/1/2002	10/31/2002	50	10
7/1/2003	12/31/2003	50	10
1/1/2004	2/28/2004	50	10
7/1/2004	12/31/2004	50	10
1/1/2005	2/28/2005	50	9
7/1/2005	12/31/2005	50	9
1/1/2006	2/28/2006	50	9
7/1/2006	12/31/2006	50	9
1/1/2007	2/28/2007	50	9
7/1/2007	12/31/2007	50	9
1/1/2008	2/28/2008	50	9
7/1/2008	12/31/2008	50	9
1/1/2009	2/28/2009	50	9
7/1/2009	12/31/2009	50	9
1/1/2010	2/28/2010	50	9
7/1/2010	12/31/2010	50	9
1/1/2011	2/28/2011	50	9
7/1/2011	12/31/2011	50	9
1/1/2012	2/28/2012	50	9
7/1/2012	12/31/2012	50	9
1/1/2013	2/28/2013	50	9
7/1/2013	12/31/2013	50	9
1/1/2014	2/28/2014	50	9
7/1/2014	12/31/2014	50	9
1/1/2015	2/28/2015	50	9
7/1/2015	12/31/2015	50	9
1/1/2016	2/28/2016	50	9
7/1/2016	12/31/2016	50	9
1/1/2017	2/28/2017	50	9
7/1/2017	12/31/2017	50	9

Table S5. Frequency table showing the number of focus group participants in each of four stakeholder groups who referred to five aspects of New Jersey recreational fishing regulations: bag limits, minimum length limits, gaps between seasons or “blackout periods,” season length, season timing, and slot limits. The “associated businesses” stakeholder group includes tackle shops and marinas, members of the fishing media, and other industry representatives.

Stakeholder group	Bag limits	Minimum length limits	Season gaps	Season length	Season timing	Slot limit*
Associated businesses	5	4	5	4	5	2
Charter boat sector	5	4	2	5	6	3
Party boat sector	2	6	4	3	4	1
Private angler	3	3	2	1	3	0
Total	18	24	18	17	23	7

* Slot limits define an intermediate size range allowable for harvest. A slot limit for summer flounder is a popular management proposal that was spontaneously brought up during several of the focus groups. Slots limits are not, however, part of the current slate of regulatory options.

Table S6: Species used to define bottomfish trips in the VTR data. Reports listing capture of at least one of these species were retained for analysis.

Bottom fish common name	Scientific name
Atlantic cod	*Gadus morhua*
Black sea bass	*Centropristis striata*
Conger eel	*Conger oceanicus*
Oyster toadfish	*Opsanus tau*
Red hake	*Urophycis chuss*
Scup	*Stenotomus chrysops*
Sea robin	*Prionotus carolinus*
Summer flounder	*Paralichthys dentatus*
Tautog	*Tautoga onitis*
Triggerfish	*Balistes capriscus*

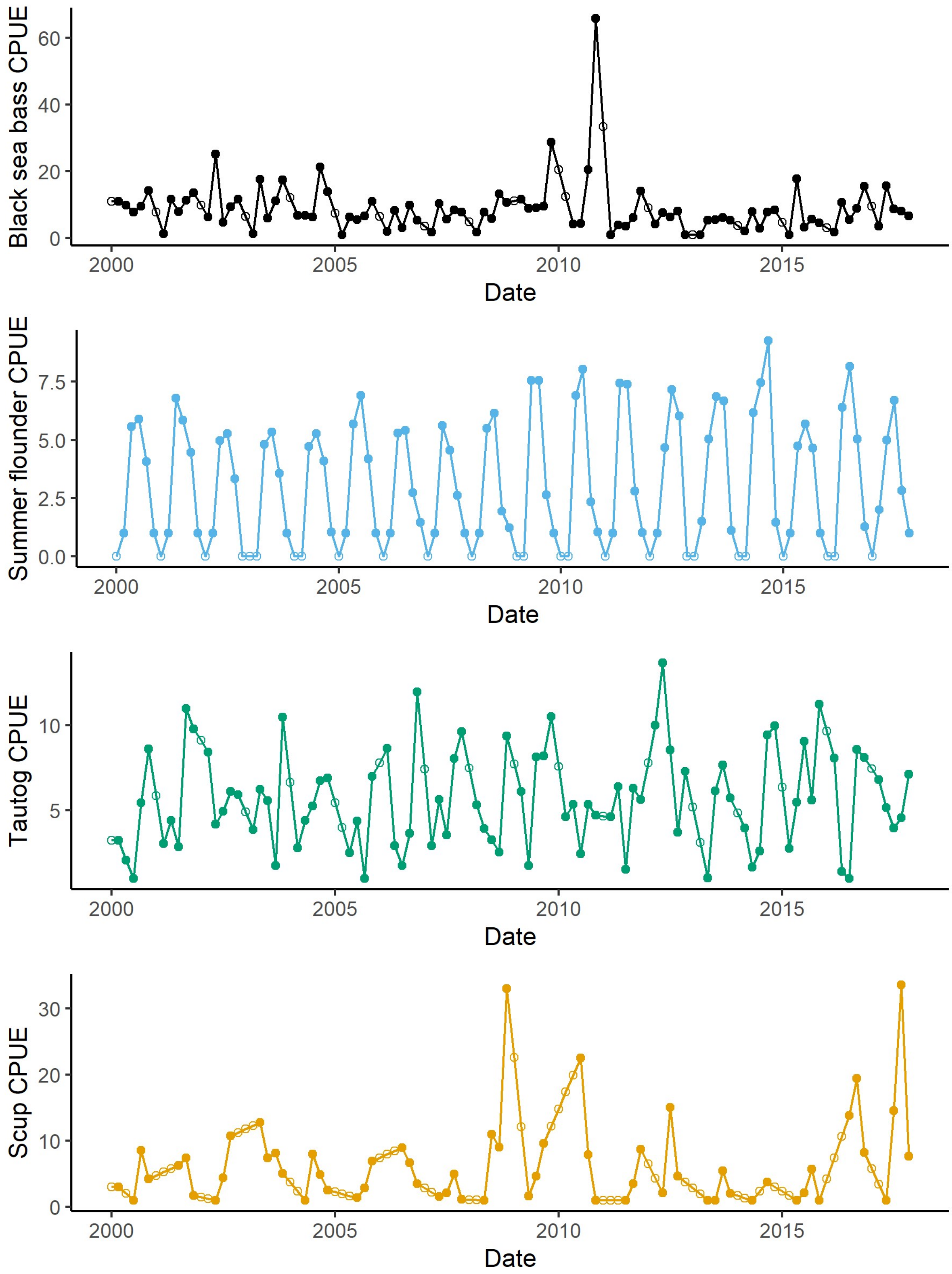

Figure S1: Mean catch per trip for each of the four focal species based on MRIP access point intercept data. Catch rates are estimated by two-month wave of sampling. Empty circles indicate imputed values. Because the scup catch rates contained so many imputed values, they were not included as predictors in the ARMA models.

Table S7: Breusch-Godfrey test results for serial autocorrelation of residuals up to lag 105 for all best-fitting models.

Model	Chi Squared value	P value
Blackout effect--charter anglers	95.265	0.7413
Species availability--party anglers	109.25	0.3687

Table S8: Coefficients of best-fitting model (blackout effect) to charter boat fishing effort time series, including the model's seasonal component. Species-specific regulations and catch rates are indicated by the following abbreviations: black sea bass (BSB), summer flounder (SMF), tautog (TOG), and scup (SCP). DF=870

Coefficient	Estimate	Standard error	T value	P value
AR1	**0.834**	**0.182**	**4.590**	**<0.0001**
AR2	-0.021	0.071	-0.297	0.766
AR3	**-0.157**	**0.050**	**-3.126**	**0.002**
AR4	**0.132**	**0.035**	**3.794**	**0.0002**
MA1	**-0.508**	**0.182**	**-2.797**	**0.005**
Intercept	**2.203**	**0.760**	**2.897**	**0.004**
BSB PL	0.004	0.005	0.733	0.464
SMF PL	0.018	0.022	0.852	0.394
TOG PL	0.032	0.025	1.307	0.192
SCP Open	0.229	0.152	1.507	0.132
Something open	**1.954**	**0.740**	**2.641**	**0.008**
N blackout days	0.024	0.017	1.465	0.143
Something open * N blackout days	-0.019	0.017	-1.170	0.242
SMF CPUE	0.010	0.029	0.350	0.727
BSB CPUE	0.007	0.006	1.069	0.285
TOG CPUE	-0.017	0.019	-0.902	0.367
Sine 1	**-1.733**	**0.125**	**-13.880**	**<0.0001**
Cosine 1	**-1.783**	**0.152**	**-11.723**	**<0.0001**
Sine 2	**-0.832**	**0.079**	**-10.495**	**<0.0001**
Cosine 2	**0.662**	**0.070**	**9.406**	**<0.0001**
Sine 3	**-0.155**	**0.059**	**-2.612**	**0.009**
Cosine 3	**0.469**	**0.057**	**8.297**	**<0.0001**

Table S9: Variance inflation factors for the main effect predictors of the blackout effect model for the charter boat time series. Species-specific regulations and catch rates are indicated by the following abbreviations: black sea bass (BSB), summer flounder (SMF), tautog (TOG), and scup (SCP).

Predictor main effects	VIF
Sine 1	4.45
Cosine 1	7.94
Sine 2	1.75
Cosine 2	1.42
Sine 3	1.24
Cosine 3	1.11
BSB PL	1.91
SMF PL	4.20
TOG PL	2.56
SCP Open	3.99
Something Open	1.39
N blackout days	2.01
SMF CPUE	5.13
BSB CPUE	1.23
TOG CPUE	1.35

Table S10: Coefficients of best-fitting model (species availability) to party boat fishing effort time series, including the model's ARMA and seasonal components. Species-specific regulations and catch rates are indicated by the following abbreviations: black sea bass (BSB), summer flounder (SMF), tautog (TOG), and scup (SCP). DF=870

Coefficient	Estimate	Standard error	T value	P value
AR1	**0.772**	**0.060**	**12.794**	**<0.0001**
MA1	**-0.537**	**0.079**	**-6.761**	**<0.0001**
Intercept	**5.745**	**0.168**	**34.228**	**<0.0001**
BSB PL	**0.050**	**0.010**	**5.050**	**<0.0001**
SMF PL	**0.227**	**0.045**	**5.089**	**<0.0001**
TOG PL	**0.141**	**0.033**	**4.283**	**<0.0001**
SCP Open	**-0.994**	**0.268**	**-3.712**	**0.0002**
BSB PL x N species available	**-0.014**	**0.004**	**-3.880**	**0.0001**
SMF PL x N species available	**-0.047**	**0.014**	**-3.474**	**0.001**
TOG PL x N species available	**-0.034**	**0.013**	**-2.506**	**0.012**
SCP PL x N species available	**0.495**	**0.095**	**5.185**	**<0.0001**
SMF CPUE	0.005	0.023	0.219	0.827
BSB CPUE	0.004	0.004	0.923	0.356
TOG CPUE	**0.030**	**0.012**	**2.444**	**0.015**
Sine 1	**-0.899**	**0.087**	**-10.334**	**<0.0001**
Cosine 1	**-1.003**	**0.110**	**-9.141**	**<0.0001**
Sine 2	0.080	0.058	1.370	0.171
Cosine 2	**0.370**	**0.048**	**7.630**	**<0.0001**
Sine 3	**-0.087**	**0.044**	**-1.987**	**0.047**
Cosine 3	0.006	0.040	0.153	0.878
Sine 4	-0.006	0.037	-0.158	0.875
Cosine 4	0.019	0.033	0.585	0.559
Sine 5	**0.074**	**0.033**	**2.255**	**0.024**
Cosine 5	0.050	0.033	1.479	0.140
Sine 6	**-0.065**	**0.028**	**-2.360**	**0.018**
Cosine 6	**0.065**	**0.028**	**2.327**	**0.020**
Sine 7	**0.062**	**0.027**	**2.295**	**0.022**
Cosine 7	-0.003	0.028	-0.094	0.925
Sine 8	**0.078**	**0.026**	**2.977**	**0.003**
Cosine 8	-0.037	0.025	-1.449	0.148
Sine 9	**-0.049**	**0.025**	**-1.985**	**0.047**
Cosine 9	0.009	0.025	0.363	0.717
Sine 10	0.038	0.024	1.562	0.119
Cosine 10	0.042	0.024	1.724	0.085

Table S11: Variance inflation factors for the main effect predictors of the species availability model for the party boat time series. Species-specific regulations and catch rates are indicated by the following abbreviations: black sea bass (BSB), summer flounder (SMF), tautog (TOG), and scup (SCP).

Predictor main effects	VIF
Sine 1	5.03
Cosine 1	9.91
Sine 2	1.83
Cosine 2	1.46
Sine 3	1.24
Cosine 3	1.11
Sine 4	1.23
Cosine 4	1.07
Sine 5	1.20
Cosine 5	1.24
Sine 6	1.01
Cosine 6	1.03
Sine 7	1.06
Cosine 7	1.07
Sine 8	1.06
Cosine 8	1.01
Sine 9	1.01
Cosine 9	1.01
Sine 10	1.01
Cosine 10	1.01
BSB PL	1.23
SMF PL	4.73
TOG PL	2.28
SCP Open	5.27
SMF CPUE	6.46
BSB CPUE	1.24
TOG CPUE	1.37

Table S12: Coefficients of the species availability model fit to the party boat fishing effort time series. The summer flounder-associated regulations were removed as predictors to detect bias in coefficient values associated with multicollinearity. Most coefficients were unchanged, but no significant effect between tautog possession limit and the number of species open was found in this model fit. Species-specific regulations and catch rates are indicated by the following abbreviations: black sea bass (BSB), tautog (TOG), and scup (SCP).

Coefficient	Estimate	Standard error	T value	P value
AR1	**0.722**	**0.074**	**9.722**	**<0.0001**
MA1	**-0.474**	**0.096**	**-4.935**	**<0.0001**
Intercept	**6.092**	**0.141**	**43.330**	**<0.0001**
BSB PL	**0.038**	**0.009**	**4.463**	**<0.0001**
TOG PL	**0.096**	**0.032**	**2.965**	**0.003**
SCP Open	**-0.973**	**0.264**	**-3.692**	**0.000**
BSB PL x N species available	**-0.010**	**0.003**	**-3.366**	**0.001**
TOG PL x N species available	-0.013	0.013	-0.991	0.322
SCP PL x N species available	**0.405**	**0.093**	**4.333**	**<0.0001**
BSB CPUE	0.003	0.004	0.705	0.481
TOG CPUE	**0.034**	**0.012**	**2.750**	**0.006**
Sine 1	**-1.001**	**0.078**	**-12.851**	**<0.0001**
Cosine 1	**-1.266**	**0.070**	**-18.121**	**<0.0001**
Sine 2	0.098	0.057	1.731	0.084
Cosine 2	**0.477**	**0.045**	**10.519**	**<0.0001**
Sine 3	0.004	0.042	0.089	0.929
Cosine 3	-0.022	0.041	-0.531	0.596
Sine 4	**-0.076**	**0.037**	**-2.051**	**0.041**
Cosine 4	0.026	0.034	0.776	0.438
Sine 5	**0.098**	**0.034**	**2.883**	**0.004**
Cosine 5	0.043	0.031	1.373	0.170
Sine 6	**-0.063**	**0.029**	**-2.185**	**0.029**
Cosine 6	**0.057**	**0.029**	**1.952**	**0.051**
Sine 7	**0.056**	**0.027**	**2.039**	**0.042**
Cosine 7	0.017	0.027	0.633	0.527
Sine 8	**0.082**	**0.027**	**3.041**	**0.002**
Cosine 8	-0.032	0.026	-1.217	0.224
Sine 9	**-0.056**	**0.025**	**-2.220**	**0.027**
Cosine 9	-0.006	0.025	-0.217	0.828
Sine 10	0.043	0.025	1.734	0.083
Cosine 10	0.035	0.025	1.400	0.162

Table S13: Variance inflation factors for the main effect predictors of the species availability model for the party boat time series with summer flounder season predictors removed from the analysis. Species-specific regulations and catch rates are indicated by the following abbreviations: black sea bass (BSB), tautog (TOG), and scup (SCP).

Predictor main effects	VIF
Sine 1	3.75
Cosine 1	2.49
Sine 2	1.68
Cosine 2	1.20
Sine 3	1.09
Cosine 3	1.11
Sine 4	1.10
Cosine 4	1.04
Sine 5	1.19
Cosine 5	1.03
Sine 6	1.01
Cosine 6	1.02
Sine 7	1.02
Cosine 7	1.02
Sine 8	1.06
Cosine 8	1.01
Sine 9	1.01
Cosine 9	1.01
Sine 10	1.01
Cosine 10	1.01
BSB PL	1.13
TOG PL	2.23
SCP Open	5.23
BSB CPUE	1.23
TOG CPUE	1.35