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FEATURED PAPER

Evaluating the Impact of Recreational Harvest and Management Strategies for Bay Scallops *Argopecten irradians concentricus* in a Florida Gulf Coast Management Zone

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Abstract
Since 1994, the fishery for bay scallops *Argopecten irradians concentricus* in Florida has been limited to a recreational fishery that operates during the summer, before the spawning season in fall. Recent growth of the fishery necessitates a study of the effect of this increased exploitation on the bay scallop population. The study focused on one management zone, centered on the community of Steinhatchee, that is known for high rates of exploitation. Within this zone, we created a model of bay scallop harvest using fishery-independent and fishery-dependent survey methods and evaluated the risk of extirpation of the stock. We found that the fishery in the zone functions as a derby, with most harvest effort occurring when the season opens, followed by a steady decline throughout the season. Effort estimates suggest that 21,579 vessels, or 82,398 people, from 94% of Florida's counties and 16 other states participated in the 2018 season in the Steinhatchee zone. The influx of harvesters generated approximately US$1.8 million in revenue for this small coastal community and resulted in an estimated fishing mortality of 57–72% of the population in the zone. The exploitation rate of the fishery in 2018 exceeded 0.4, suggesting that the fishery may be unable to sustain itself under current conditions. We evaluated management strategies and found that the bay scallop

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population in this zone would be in danger of being extirpated if harvest effort doubled, suggesting the need for regular monitoring of effort in this fishery in this zone and probably in the fishery statewide.

The distribution of the Florida bay scallop *Argopecten irradians concentricus* once extended from West Palm Beach to Biscayne Bay in southeastern Florida and from Florida Bay westward to Pensacola Bay in the Gulf of Mexico (Clarke 1965; Waller 1969). Historically abundant bay scallop populations in Florida have declined in recent decades (Arnold et al. 1998, 2005; Marelli and Arnold 1999; Geiger et al. 2017), possibly due to a combination of decreasing water quality, red tides, overfishing, recruitment failure, and habitat loss (Barber and Blake 1983; Arnold and Marelli 1991; Blake et al. 1993; Arnold et al. 1998; Yarbro and Carlson 2013). Thus, bay scallops in Florida today occur only along the Gulf of Mexico coast, where they are limited to local subpopulations in seagrass beds separated by areas of low salinity (<20‰) (Arnold et al. 1998; Geiger et al. 2017).

Bay scallops are a difficult species to manage because they rarely live longer than 22 months and typically spawn only once (Loosanoff and Davis 1963; Sastry 1965; Castagna and Duggan 1971). Spawning in Florida is thought to peak in fall or early winter (Barber and Blake 1981, 1985, 2016), but recruitment monitoring indicates that spawning can be protracted and can also occur, at a low level, in spring or early summer (Arnold et al. 1998; Bologna 1998; Geiger et al. 2010). Bay scallops are strongly associated with seagrass because juveniles and adults typically remain within the seagrass beds in which they settled as spat (Barber and Blake 1983). As juveniles attached to seagrass, bay scallops are vulnerable to predation by epifaunal invertebrates, such as amphipods, isopods, and shrimp (Lefcheck et al. 2014). Once bay scallops reach a size of 15–25 mm, they migrate to the sediment surface (Tettelbach 1986) and are vulnerable to benthic predators, such as crabs and whelks (Ambrose and Irlandi 1992). Bay scallops in Florida are distributed as a hierarchical, complex, mixed-model metapopulation with a core source population, but in every population is a subpopulation that can act as a local source of recruitment (Bert et al. 2014).

Commercial landings of Florida bay scallops began to decline in the 1960s (Joyce 1982). Degradation of habitat quantity and quality, combined with overfishing leading to recruitment failure (Arnold and Marelli 1991; Blake et al. 1993), led to the decline in bay scallop landings as has been observed in the collapse of other scallop fisheries (Orensanz et al. 2016). The declines in bay scallop landings in Florida prompted the first fishery management actions in 1985 by the Florida Fish and Wildlife Conservation Commission, which placed gear restrictions and harvest limits on the recreational and commercial bay scallop fisheries (FWC 2019). These measures did not lead to the recovery of bay scallop populations, so the commercial fishery was closed statewide in 1994.

The recreational fishery was restricted in 1994 to a small zone in state waters encompassing the core of the population (i.e., north of the Suwannee River to the Alabama state line). In 1995, the recreational fishery harvest limit was decreased from 5 gallons (1 gallon = 3.79 L) of whole bay scallops per person per day to its current limit of 2 gallons per person per day or 1 pint (0.47 L) of shucked bay scallop meat per person per day. Additionally, a vessel limit for bay scallops was established in 1995 of 10 gallons of whole bay scallops per day or one-half gallon of shucked bay scallop meat per day. Scallop harvesters typically use 5-gallon buckets and pint or gallon sandwich bags to measure their harvest of whole bay scallops or scallop meats, respectively. The recreational harvest in 1995 was further limited to collection by hand or dip net, and most harvesters in Florida choose to collect scallops by snorkeling in shallow water (<3 m in depth). No limit has ever been placed on the number of vessels or recreational harvesters that can participate in the fishery. In addition, there is no limit on the total amount of scallops that a recreational harvester can collect throughout the season. The 1995 season for bay scallop harvest was set to begin July 1 and end August 31 to accommodate the tradition of collecting bay scallops as a family activity during the summer. Fishery-independent monitoring of the bay scallop population since 1994 has revealed substantial year-to-year variability in local subpopulation densities, with the overall population remaining at a relatively low but stable density (Geiger et al. 2017). Although the recreational season typically begins around the July 4th holiday and ends around the Labor Day holiday, management of bay scallops from 1994 to 2015 primarily involved adjusting the average length of the recreational season, which was 83 ± 11 d (mean ± SD) during that period. Most recently, in 2016 the Florida Fish and Wildlife Conservation Commission created four management zones along the Gulf of Mexico coast, each having a unique recreational bay scallop harvest season duration, ranging from 10 to 88 d (FWC 2019). These changes in the regulation of this resource were based largely on stakeholder input and the desire for the expansion of tourism in these economically depressed coastal communities.

The harvest of bay scallops in Florida occurs in the summer before bay scallops are likely to have spawned.

Thus, the Florida bay scallop fishery is unlike all other bay scallop fisheries in the United States in which bay scallops are not harvested until after their first spawning season at approximately 15 months of age (MacKenzie 2008; Robinson et al. 2016). For instance, in Massachusetts commercial and recreational harvest of bay scallops occurs from October to March (https://www.mass.gov/service-details/recreational-saltwater-fishing-regulations), while harvest of bay scallops in New York occurs from November to March (https://www.dec.ny.gov/outdoor/29870.html). Although the harvest of bay scallops in North Carolina has been closed indefinitely because the fishery is considered depleted, the recreational and commercial fishery historically operated from January to April (NCDMF 2019). In addition, the Northeast bay scallop fisheries implement a minimum size limit by requiring that harvested bay scallops possess a well-defined annual growth ring, although local towns may have additional size limit restrictions. However, most Florida bay scallops only live a maximum of 18 months and therefore do not have an annual growth ring.

Despite its long history, the recreational bay scallop fishery in Florida has been evaluated in only one study (Greenawalt-Boswell et al. 2007), and that study did not directly measure bay scallop harvest. Those authors used fishery-independent estimates of pre- and postseason bay scallop densities in areas open and closed to bay scallop harvest, which allowed estimates of fishing and natural mortality. Yet only 40% of those surveys showed a significant decrease in bay scallop densities over the course of the season, perhaps suggesting limitations in the methodology used to estimate bay scallop densities. The authors used aerial surveys to count vessels possibly harvesting bay scallops and assumed that all vessels collected the regulation limit of bay scallops. They found that natural mortality was substantially higher than fishing mortality, and simulations suggested that the levels of bay scallop harvest measured would have been unlikely to extirpate healthy populations of bay scallops at the time. The recent creation of the four management zones, with different season lengths and increasing exploitation of the resource, has necessitated the investigation of the exploitation dynamics of this resource.

The purpose of the present study was to model the impact of the Florida bay scallop harvest on the population in one of the four management zones (Figure 1). The study developed model estimates of population size and sources of mortality from a combination of fishery-dependent and fishery-independent data sets. Recreational removals during seasonal harvest were modeled to develop fishery mortality estimates that were compared with natural mortality, as estimated from fishery-independent data. The model was used further to evaluate the accuracy of harvest estimates by comparing the model estimate with our fishery-independent estimate of abundance. Finally, we evaluated different management strategies, by modeling different season lengths and harvest efforts, to determine the effect on population size at the end of the season, resulting in an estimate of fall spawning-stock biomass.

STUDY SITE

This study focused on one of Florida's four management zones for the bay scallop, the one centered in the Steinhatchee region, along the Gulf coast of Florida from the Suwannee River north to the Fenholloway River (Figure 2). This zone was chosen because it has a relatively stable bay scallop population and is a core source population, acting as an integral part of the metapopulation by providing recruits to other populations (Bert et al. 2014). Furthermore, this zone has one of the longest histories of recreational bay scallop harvest in Florida and is a popular destination for recreational harvesters. Aerial surveys conducted in 2016 and 2017 by the Florida Fish and Wildlife Conservation Commission's Fish and Wildlife Research Institute (FWRI; unpublished data) suggest that the number of vessels harvesting bay scallops in this zone has increased since the zone was last surveyed in 2002 by Greenawalt-Boswell et al. (2007). Additionally, seagrass acreage in this zone declined significantly during 2006–2015, and mapping data suggest that this decline began as early as 1990 (Yarbro and Carlson 2018). Thus, both the status of the bay scallop population in the zone and the impact of increased recreational harvest on this core population needed to be evaluated. The present study sought to further our understanding of the vulnerability of the core population to harvest and of any threats to the structure of the Florida metapopulation.

METHODS

Fishery-independent methods.— Fishery-independent methods used scuba divers to evaluate the preseason and postseason (season studied was June 16 to September 10, 2018) density of bay scallops along transects located in one-third of the zone. This smaller survey area was chosen because the FWRI had surveyed it intermittently since 1994 using methods similar to those described below, which provided a context for new data. The survey area was limited to the extent of seagrass mapped for the area in 2015 (http://geodata.myfwc.com/datasets/seagrass-habitat-in-florida) and to those portions between the depth contours of 0.1 m and 1.83 m. Surveys were conducted in 400-m^2 grid cells that were randomly selected in the survey area. Two divers counted bay scallops and measured their shell height along a 1-m swath on either side of a 100-m transect positioned within a grid cell. We conducted the

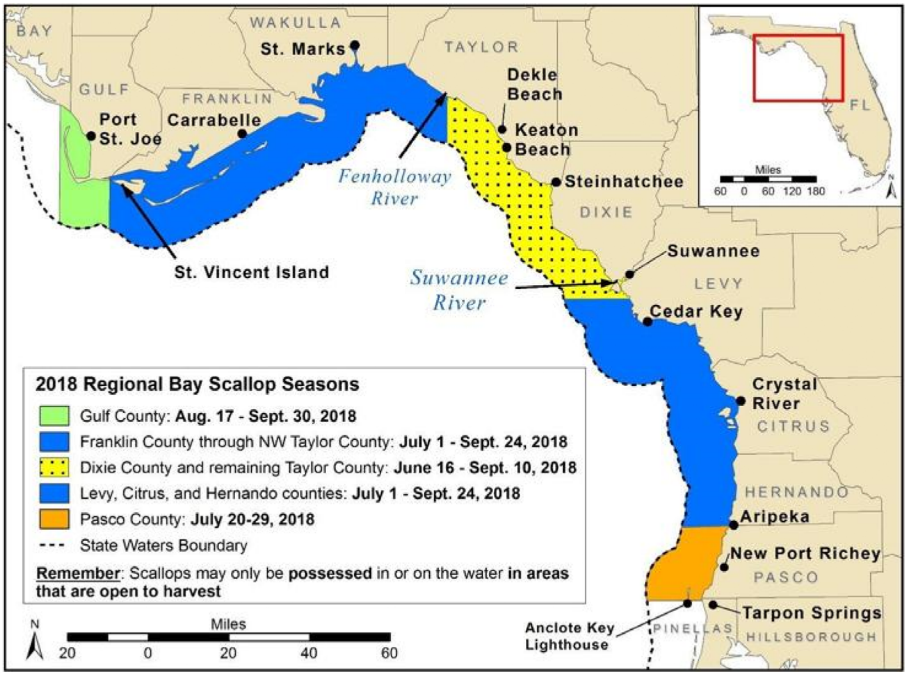

FIGURE 1. Map of the four management regions established in 2018 by the Florida Fish and Wildlife Conservation Commission for the harvest of bay scallops. The season start and end dates are different for each region, but the harvest limits established for bay scallops were the same for all regions. Source: https://myfwc.com/fishing/saltwater/recreational/bay-scallops/.

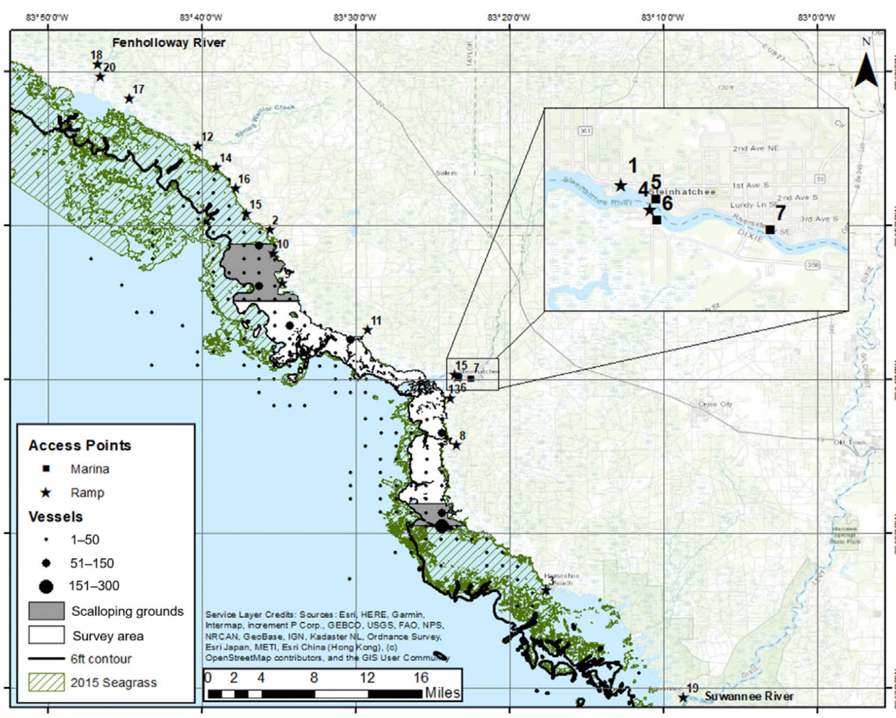

FIGURE 2. The Steinhatchee zone extends from the Fenholloway River to the Suwannee River and is limited to the extent of the mapped seagrass area. Marinas and ramps in the study area are numbered according to their weighted rank (Table 1). The area surveyed by divers (i.e., the survey area) is approximately 105 km^2 and is centered on the Steinhatchee River, extending to the 1.83-m (6-ft) depth contour. The distribution of scalloping vessels was used to determine the extent of the scalloping grounds, which include the survey area (white shading) and extend north and south of it (gray shading), covering approximately 149 km^2.

preseason survey during June 4–10, running a transect in 89 different cells, and the postseason survey during September 14–19 in 100 grid cells. During preseason surveys, a novice snorkeler preceded an experienced scuba diver along one side of the 100-m transect and counted the number of bay scallops observed along a 1-m swath. The catch per unit effort (scallops per hour) by the novice snorkeler was used to develop a detectability estimate for a recreational scalloper because most recreational harvesters snorkel to collect scallops.

Fishery-dependent methods.— Aerial surveys counted vessels seen on the water and trailers seen at boat ramps during the season for estimating harvest effort in the Steinhatchee zone. Aerial surveys were done from approximately 1100 to 1300 hours on 15 d throughout the season. During an aerial survey, an observer counted the number of boat trailers at 17 ramps as the plane traveled from north to south throughout the zone (Table 1; Figure 2). On the return flight, from south to north, the observer counted all vessels visible within approximately 5 km of the coastline.

Interviews with harvesters returning to boat ramps and marinas were conducted by creel samplers throughout the season to evaluate bay scallop harvest. Creel sampling was done on 31 d during the season, including 13 weekend days and 18 weekdays, from approximately 0900 to 1700 hours. Before we began creel surveys, we ranked each ramp or marina by summing the values (ranked 1 to 4) of each of the following characteristics, taken from the National Oceanic and Atmospheric Administration Fisheries Site Register (https://www.st.nmfs.noaa.gov/msd/html/siteRegister.jsp): number of trailer parking spaces, number of slips, number of ramps, average monthly fishing pressure based on the estimated number of anglers expected to complete a fishing trip at the site during the season, and distance to seagrass beds (calculated in ArcGIS) (Table 1). We sampled only at the seven ramps and marinas with the highest-ranked values to increase the likelihood that samplers would encounter vessels that had harvested scallops. Creel samplers were assigned to the ramps and marinas that were selected, based on the above ranks, using an Excel macro (https://www.mathscinotes.com/2012/04/randomly-choosing-a-winner-from-a-weighted-list-with-excel/). We sampled two to six ramps and marinas on a given day, depending on the anticipated number of harvesters.

Creel samplers recorded the number of boat trailers in the parking lot at boat ramps at the beginning and end of a sampling day. In addition, they recorded the number of vessels launching from the boat ramp and summed these every hour. Samplers also recorded the number of boat trailers in the parking lots of the four highest-ranked boat ramps on every day of creel sampling. Creel samplers at any of the marinas or at the Jena County boat ramp also counted the total number of vessels entering and exiting the Steinhatchee River because those locations provided a relatively unobstructed view of the river. The purpose of counting vessels entering and exiting the Steinhatchee River was to compare these counts with the vessel and trailer counts to determine if they were correlated.

Weather conditions were recorded hourly by creel samplers using one or more of the following classifications: sunny, partly cloudy (40–60% of the sky covered by clouds), mostly cloudy (>75% of the sky covered by clouds), rain, thunder, lightning, breezy (15- to 25-km/h winds), windy (>25-km/h winds), or calm (not breezy or windy). During interviews with bay scallop harvesters, creel samplers attempted to record all of the following information for each returning vessel: interview start time, activity type (bay scallop harvesting, angling, both bay scallop harvesting and angling, other activity, or refused interview), number of people on the vessel, number of people on the vessel harvesting bay scallops (exclusive of children under 18, whom we assumed were inefficient at harvesting scallops), time at which the vessel had departed the ramp or marina, number of hours spent harvesting (to the nearest half hour), number of whole bay scallops harvested, gallons of whole bay scallops harvested, pints of meat harvested if meat was extracted on board, number of harvesters on the vessel who had purchased a fishing license for the sole purpose of harvesting bay scallops, the county of residence of the people on the vessel, and whether the vessel was a bay scallop charter vessel. In addition, maps of the zone with numbered, square grid cells of 2.6 km^2 were provided to harvesters to identify the approximate locations in which they had harvested. Finally, creel samplers took a picture of 5 to 10 whole bay scallops randomly selected from vessels for which interviews were conducted, if time permitted. Images of bay scallops were analyzed using ImageJ 1.52i (https://imagej.nih.gov/) to determine shell height, as measured from the hinge to the margin of the valve, of five individuals randomly selected from each picture.

Additional information on weather and sea state during the season in the zone was collected from online sources for incorporation into a model of harvest. Weekly optical water quality parameters that approximate water turbidity (chlorophyll *a*, colored dissolved organic matter, and particulate backscattering) and sea surface temperature were obtained for nine stations in the Steinhatchee zone from the optical oceanography laboratory at the University of South Florida (https://optics.marine.usf.edu/projects/vb/BIGBEND/St/index.html). Weather data, including temperature, precipitation, humidity, visibility, wind direction, and wind speed, were gathered from the National Centers for Environmental Information's Integrated Surface Dataset for two local sources (Perry–Foley Airport and Cross City Airport).

TABLE 1. Steinhatchee zone boat ramp and marina characteristics listed from highest to lowest weighted rank based on the number of boat ramps, number of trailer spaces or boat slips, minimum distance to seagrass beds, and average monthly fishing pressure during the bay scallop season (i.e., June 16–September 10, 2018).

Ramp name	Rank	Ramps	Trailer spaces or boat slips	Distance to seagrass (km)	Fishing pressure	Latitude	Longitude
Steinhatchee boat ramp	1	3	42	2.882	1.100	29.672883	−83.392500
Keaton Beach boat ramp	2	2	100	1.765	0.992	29.829700	−83.592783
Horseshoe Beach boat ramp	3	2	20	0.108	1.283	29.439933	−83.293017
Jena County boat ramp	4	2	50	2.927	0.833	29.670133	−83.389117
Sea Hag Marina	5	0	50	4.328	1.083	29.671300	−83.388483
Good Times Marina	6	0	50	3.115	0.558	29.668900	−83.388317
River Haven Marina	7	0	30	4.385	1.075	29.667850	−83.375400
Rocky Creek boat ramp	8	1	24	1.321	0.817	29.596267	−83.390117
Hagen's Cove boat ramp	9	1	6	0.057	0.200	29.772400	−83.579417
Dark Island boat ramp	10	1	10	7.843	0.783	29.803900	−83.588517
Dallus Creek boat ramp	11	1	10	2.167	0.300	29.721500	−83.486400
Spring Warrior boat ramp	12	1	6	1.511		29.920430	−83.670800
Sand Ridge boat ramp	13	1	4	1.051		29.647490	−83.396840
Yates Creek boat ramp	14	1	6	0.354		29.897530	−83.650750
Deakle Beach boat ramp	15	1	5	0.32		29.847178	−83.618182
Jabo boat ramp	16	1	5	0.307		29.874924	−83.629963
Spring Creek boat ramp	17	1	5	2.825		29.972360	−83.745080
Fenholloway River boat ramp	18	1	5	7.308		30.009510	−83.779350
Suwanee boat ramp	19	1	1	6.215		29.323710	−83.144330
Fenholloway boat ramp	20	1	10	5.101		29.995770	−83.776240

Statistical methods.— Except where otherwise noted, statistical analyses were conducted with the Fathom toolbox (Jones 2015) and implemented using MATLAB software (version R2019b) with permutation-based tests using 1,000 permutations and significance levels (α) set at 0.05 for all analyses involving hypothesis testing. We interpolated bay scallop densities within grid cells to the extent of the seagrass layer in the survey area in ArcGIS software (version 10.6.1) using the inverse-distance-weighted tool to estimate initial bay scallop population size (N_0) and final population size (N_t) after the bay scallop season. Average bay scallop density was also interpolated outside of the survey area (105 km^2) to the larger area (149 km^2) of substantial harvest as recorded by creel samplers, hereafter referred to as the scalloping grounds (Figure 2).

We compared preseason and postseason bay scallop shell heights collected from diver surveys to those measured during creel surveys to determine whether harvesters collected bay scallops that were smaller or larger than the average size available in the population. Specifically, shell heights from the first 4 d and the last 4 d of creel surveys were compared, respectively, with preseason and postseason diver-survey shell heights using a two-tailed t-test with permutation tests of significance for the t-statistic. We used 4 d of creel sampling data in both tests to increase the sample size of shell-height data from creel sampling.

The following equation from Geiger et al. (2006) was used to relate shell height (SH; mm) to the number of bay scallops in a gallon (S_{gal}), which allowed us to convert shell height to gallons:

$$S_{gal} = [(-6.704 \cdot SH) + 480.96]/2. \qquad (1)$$

We constructed a linear regression model relating S_{gal} and date and used permutation tests of significance for the F- and t-statistics. The linear equation predicting S_{gal} was used to convert harvest in gallons to number of bay scallops. Harvest regulations state that 1 pint of adductor muscle meat is equivalent to 2 gallons of whole bay scallops, and Geiger et al. (2006) showed that this was true for most months of the season in the Steinhatchee zone. Thus, this linear equation was adapted to convert harvest reported in pints of adductor meat to the number of bay scallops, by multiplying the equation by two.

We used bootstrapping to estimate catch per unit effort (CPUE; number of bay scallops collected per hour) in terms of the average number (with 95% CIs) of (1) gallons collected by a vessel (G_V), (2) gallons collected by a harvester (G_H), (3) gallons collected by a harvester in an hour

(G_{HH}), and (4) harvesters on a vessel (H_V). The curve-fitting function in MATLAB, which uses the linear–least squares method, was used to fit a linear model to these measures of CPUE with date as the predictor variable. Additionally, we compared CPUE from the fishery-independent novice snorkeler surveys to that from our creel surveys on opening day.

To estimate harvest effort (number of vessels on the water) on days for which no aerial survey was conducted, we determined whether there was a significant relationship between trailer counts and vessel counts. Pearson correlation tests with permutation-based significance testing were used to evaluate the correlation between trailer counts at all ramps combined and the daily vessel count for the 15 d on which an aerial survey was conducted. Additionally, we used Pearson correlation tests to determine whether the number of vessels exiting or entering the Steinhatchee River could be related to the number of vessels on the water, as estimated using the aerial surveys. The boat ramp with the highest correlation to vessel count was then used to determine the linear relationship to vessel counts and thus calculate vessel counts on days on which no aerial survey was conducted. Vessel counts were analyzed using a one-way ANOVA with permutation-based significance testing to determine whether there was a significant difference in vessel counts among days of the week.

Water turbidity variables were standardized and ordinated using a principal coordinate analysis with a Euclidean-based dissimilarity matrix to reduce the number of variables in the final analysis. Because the ordinated turbidity variables were found to be an important predictor of CPUE in 2018, we calculated bootstrapped average, annual chlorophyll *a* from 2002 to 2019 during the season to obtain a trend in turbidity. We chose to use chlorophyll *a* as a proxy for ordinated water turbidity (although it does not consider all measures of turbidity) because it had the largest sample size of the turbidity variables for the sampling period.

Weather conditions recorded by creel samplers were reduced to percentages based on the total number of observations recorded in a day. These weather condition variables, and the temperature measurements from the Cross City Airport and Perry–Foley Airport, were also standardized and ordinated using separate principal coordinate analyses. We combined all weather variables with the independent variables of date and day of the week to perform stepwise selection of all independent variables via forward addition based on Akaike information criterion (AIC). Model selection was used to select the optimal subset of independent variables for the following dependent variables determined from the creel surveys: (1) the number of bay scallops collected by a vessel (S_V), (2) the number of vessels on the water (V), and (3) the proportion of vessels harvesting bay scallops (P_r). Following AIC model selection, linear multiple-regression models using the optimal subset of independent variables were constructed for each of those dependent variables. We conducted permutation tests of significance for the F- and t-statistics to evaluate model fit. Fitted values of S_v, V, and P_r were multiplied together to estimate total 2018 bay scallop harvest (C) in the survey area.

The bay scallop population simultaneously experiences fishing mortality and natural mortality, so the bay scallop fishery is considered a type II fishery (Ricker 1975). We calculated seasonal total mortality (A) using the estimates of initial population size (N_0) and final population size (N_t) after the 87-d bay scallop season as estimated by the fishery-independent diver surveys. These calculations were completed using the population sizes estimated from the survey area and from the scalloping grounds after Ricker (1975) as follows:

$$A = 1 - \frac{N_t}{N_0}. \tag{2}$$

Seasonal fishing mortality (u) was calculated using the fishery-dependent-survey-derived estimate of harvest (C) and fishery-independent-survey-derived initial population size (N_0) as follows:

$$u = CN_0. \tag{3}$$

Seasonal fishing mortality (u) was subtracted from seasonal total mortality (A) to calculate seasonal natural mortality (v). Next, we converted seasonal total mortality (A) into daily instantaneous total mortality (Z), with t representing season length in days, by the following:

$$Z = \frac{[-\log_e(1-A)]}{t}. \tag{4}$$

Daily instantaneous fishing mortality (F) was calculated as follows:

$$F = \frac{uZ}{A}. \tag{5}$$

Finally, we subtracted daily instantaneous fishing mortality (F) from daily instantaneous total mortality (Z) to calculate daily instantaneous natural mortality (M).

We also estimated initial population size (N_0) and the catchability coefficient (q) using a modified form of the standard Leslie–DeLury analysis (Leslie and Davis 1939; DeLury 1951), which adjusts the slope (q') when natural mortality is not negligible relative to fishing mortality (Chien and Condrey 1985). We estimated N_0 using our fishery-dependent data in this manner to compare with our estimate of N_0 obtained using our fishery-independent data. The modified form of the Leslie–DeLury equation does not rely on DeLury's approximation of the Taylor series and is given by the following:

$$\frac{C_t}{f_t} = qN_0 - q'Kt, \tag{6}$$

where C_t is catch taken during time interval t, f_t is constant fishing effort, K_t is cumulative catch to the start of interval t plus half of that taken during the interval, and q' is the absolute value of the slope of C_t/f_t regressed against K_t. This approach assumes that catch is proportional to abundance and that the population is closed.

Management strategy evaluations.— Management strategies were evaluated by conducting simulations that altered the duration of open season and harvest effort to determine their effects on estimates of mortality. Population size in each simulation was calculated using M for the survey area as follows:

$$N_t = N_{t-1}\left(e^{-M}\right) - C_{t-1}. \tag{7}$$

We then calculated seasonal and daily mortality for each simulation using equations (2)–(5).

In the first three scenarios of management strategies (Table 2), season start and end dates were adjusted (1) to extend the season 2 weeks at the end of the season (scenario 1), (2) to start the season 2 weeks later and keep the season length the same (scenario 2), or (3) to start the season 2 weeks later and end it 2 weeks early (scenario 3). These scenarios were chosen because the season start date in this zone has been adjusted seven times in the past decade to start anywhere between June 15 and July 1. In scenario 1, the models of S_v, V, and P_r were extended to estimate C for an additional 2 weeks. The number of bay scallops that can legally be harvested on June 16 is reduced by 6.88% for a season start date of July 1 due to fast bay scallop growth rates; thus, harvest in the scenarios starting on July 1 was reduced by this amount. In a fourth scenario, the season was shortened to a month and began on June 16.

Regulations changed for the 2020 bay scallop season in the Steinhatchee area to reduce the bag limit to 1 gallon per person from June 15 to June 30, followed on July 1 by an increase to the regular bag limit. We wanted to apply the model to the change in regulations that was instituted in 2020. Thus, in a fifth scenario, we evaluated the impact this management decision would have had on the 2018 bay scallop season. Additionally, in a sixth scenario, we evaluated how a permanent reduction in the limit to 1 gallon per person would affect the final population size. In a seventh scenario, we evaluated the current harvest limit by simulating that each vessel collected the maximum legal harvest limit and then recalculating the harvest. In an eighth scenario, we simulated the level of harvest effort, in terms of the increase in the number of scalloping vessels, at which the population in the survey area would be extirpated by the end of the regular season. Finally, we calculated the minimum and maximum historical starting population sizes that could be expected in this zone using FWRI preseason survey data (unpublished). In scenarios 9 and 10, we used the minimum and maximum population sizes, respectively, to determine the increase in harvest effort required to extirpate these historical populations.

RESULTS

Creel surveys were conducted on 5,163 vessels on 31 d during the bay scallop season. Survey respondents were engaged in the following activities: harvesting bay scallops (54% of survey respondents), harvesting fish (26%), harvesting fish and bay scallops (10%), and recreational boating (7%); 3% refused to be interviewed (Table 3). Sixty-seven percent of respondents reported purchasing a fishing license for the sole purpose of harvesting bay scallops (i.e.,

TABLE 2. Summary of the management strategies evaluated in simulations altering season length, season start and end dates, and harvest effort.

Scenario	Season start	Season end	Description
Normal	Jun 16	Sep 10	Normal season length and limits
1	Jun 16	Sep 25	Increase season length by 2 weeks in September
2	Jul 1	Sep 25	Start season 2 weeks later and keep season length the same
3	Jul 1	Sep 10	Start season 2 weeks later and reduce season length by 2 weeks
4	Jun 16	Jul 15	Reduce season length to 1 month
5	Jun 16	Sep 10	Reduce limit by half for first 2 weeks of season, then increase to full limit
6	Jun 16	Sep 10	Reduce limit by half for entire season
7	Jun 16	Sep 10	Every vessel collects the regulation limit
8	Jun 16	Sep 10	Increase the number of vessels to extirpate the 2018 population
9	Jun 16	Sep 10	Increase the number of vessels to extirpate the historical minimum population
10	Jun 16	Sep 10	Increase the number of vessels to extirpate the historical maximum population

TABLE 3. Responses to select creel survey interview questions addressing the following: the activities that survey respondents were engaged in, the purpose for purchasing a fishing license, how harvest was reported, and the state and/or county of origin.

Question	Responses	Percent
What activity were you engaged in?	Harvesting scallops	56
	Harvesting fish	27
	Harvesting fish and scallops	10
	Recreational boating	7
Did you purchase a license for the sole purpose of scalloping?	Yes	67
	No	33
How was harvest reported?	Gallons of whole scallops	74
	Number of whole scallops	24
	Pints of scallop meat	2
What is your state and county of origin?	Georgia	14
	Florida	84
	15 other states (individually <5% of total)	2
	Alachua County, Florida	16
	Duval County, Florida	11
	Taylor County, Florida	8
	St. Johns County, Florida	6
	59 other counties in Florida (individually <5% of total)	59

not for recreational fishing). Harvest was reported primarily in terms of gallons of whole bay scallops (74%), followed by the number of whole bay scallops (24%), and then by pints of bay scallop meat (2%). Respondents came from 16 states and from 63 of the 67 counties in Florida; we did not encounter respondents from Glades, Gulf, Hendry, or Washington counties in Florida. Fourteen percent of harvesters came from Georgia. Of respondents from Florida, 13% came from Alachua County, 9% from Duval County, 7% from Taylor County, and 5% from St. Johns County; the remaining 52% came from other Florida counties and states, each of which accounted for less than 5% of the total.

Catch per Unit Effort

The number of whole bay scallops (S_{whole}) in a gallon (S_{gal}) decreased significantly throughout the season as shell height increased ($R^2 = 0.122$, $F = 321.09$, $P < 0.001$). The relationship between S_{gal} and date (D) was used to convert measurements in gallons into whole bay scallops as follows:

$$S_{whole} = S_{gal}(-0.295D + 64.6359). \quad (8)$$

Harvest effort was evaluated in terms of gallons, not the number of whole bay scallops, because harvest regulations refer to gallons per harvester or vessel. The CPUE in terms of the number of gallons per vessel, gallons per harvester, and gallons per harvester per hour throughout the season followed similar patterns (Figure 3). Harvest effort began to increase as soon as the season opened and peaked during the July 4th holiday weekend. It then decreased, reaching its lowest point in mid to late August, after which it began to increase again, continuing to increase until the end of the season. On average, there were 3.83 harvesters on a vessel (H_v; 95% CI = 3.50–4.17), and this did not change substantially during the season:

$$H_V = -4.746 \times 10^{-04} D + 3.833. \quad (9)$$

Harvesters collected an average of 0.81 gallons of bay scallops per person (95% CI = 0.69–0.95) and 2.92 gallons (2.44–3.39) per vessel during the season; approximately 1.6% of harvesters exceeded their legal harvest limit. In comparison, harvesters on charter vessels collected an average of 1.89 gallons (1.69–2.08) per person and 7.37 gallons (6.60–8.14) per vessel. A total of 40 interviews (0.77% of total interviews) were conducted with harvesters on charter vessels, approximately 58% of them around the July 4th holiday weekend. Analysis of charter vessel harvest was not conducted due to the small number of interviews with these vessels covering a relatively short period during the season.

A novice snorkeler collected an average of 21.0 bay scallops per hour (95% CI = 14.3–27.7) during the preseason surveys. The novice snorkeler missed an average of 78.0% of the bay scallops that a more advanced scuba diver found on the same transect. Similarly, harvesters collected an average of 21.4 bay scallops per hour (19.3–23.5) on the first day of the season, which was not significantly different from the number of bay scallops per hour

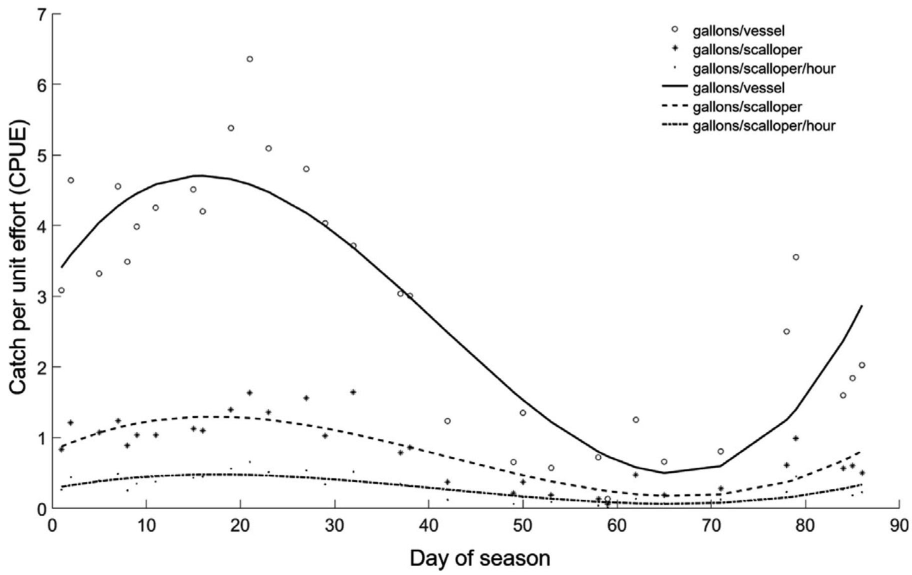

FIGURE 3. Catch per unit effort was evaluated in terms of the number of gallons per vessel (G_V), gallons per harvester (G_H), and gallons per harvester per hour (G_{HH}). The first season day corresponds to the season start date (June 16, 2018), and the last season day corresponds to the season end date (September 10, 2018). The relationships between CPUE and G_V, G_H, and G_{HH} were given by $G_V = 6.507 \times 10^{-5}D^3 - 8.028 \times 10^{-3}D^2 + 0.205D + 3.21$; $G_H = 1.834 \times 10^{-5}D^3 - 2.303 \times 10^{-3}D^2 + 0.062D + 0.814$; and $G_{HH} = 7.276 \times 10^{-6}D^3 - 9.093 \times 10^{-4}D^2 + 2.503 \times 10^{-2}D + 0.281$, where D is season day.

collected by a novice snorkeler, as the confidence intervals overlapped.

Trailer and Vessel Counts

Most trailers (70.3%, on average) were present in parking lots at boat ramps between 1000 and 1300 hours. Creel samplers conducted most of their interviews (73.3%) between 1300 and 1600 hours. Thus, aerial surveys, conducted from 1100 to 1300 hours, overlapped with the time period during which the most vessels were on the water.

Pearson correlations between trailer counts at boat ramps and vessel counts from the aerial surveys revealed that all but 5 of the 17 trailer counts at boat ramps had significant correlations with vessel counts ($P < 0.05$; Table 4). Pearson correlations between the vessel counts made as vessels were entering or exiting the Steinhatchee River with those from aerial surveys revealed that only the correlations from the Jena County boat ramp and River Haven Marina were significant ($P < 0.05$; Table 4). We used trailer counts from the Jena County boat ramp and Keaton Beach boat ramp to convert trailer counts from these ramps to vessel counts. These ramps were selected because they had the highest Pearson r correlation coefficients of the four ramps sampled on days on which no aerial survey was made. The relationship between the boat ramp trailer count (T) and vessel count (V) was $V = 12.0T + 63.8$ for the Jena County boat ramp and $V = 4.7T + 17.4$ for the Keaton Beach boat ramp.

Vessel counts, those from the aerial surveys and those from converted trailer counts, were significantly different among days of the week (df = 41, $F = 5.104$, $P = 0.002$); the highest vessel counts were observed on Wednesdays, Fridays, and Saturdays. But in 2018, July 4th fell on a Wednesday and might have skewed the vessel count for Wednesdays. Approximately twice as many vessels were observed on Fridays and Saturdays than on the other days of the week, with an average of 608 vessels (95% CI = 493–722) observed on these Fridays and Saturdays and an average of 288 vessels (228–348) on the other days of the week.

Creating a Harvest Model

Of the 13 environmental variables, 3 were selected for use in the harvest model. Variable selection for the model of CPUE (number of bay scallops harvested per vessel) resulted in the selection of two optimal variables: date and ordinated turbidity (Table 5). Date was the optimal variable selected for the model of the proportion of vessels harvesting bay scallops. The model of total vessels included both date and day of the week (Table 5).

We conducted a follow-up analysis of water turbidity because it was the only environmental variable selected in the model as an optimal variable. Chlorophyll a during the bay scallop season from 2002 through 2019 was greatest in 2005, 2012, and 2018 (Figure 4). In 2018, chlorophyll a was approximately twice as high as the average and there was no harmful algal bloom event that occurred during this time that would have affected participation in the fishery.

The multiple regression model for the number of bay scallops harvested per vessel (CPUE) showed a steady

TABLE 4. Pearson correlation *r*-values and permuted *P*-values relating the number of trailers at boat ramps, or the number of vessels entering or exiting the Steinhatchee River as observed at boat ramps or marinas, to the number of vessels on the water. Ramps and trailers are sorted according to Pearson *r*-values from highest to lowest.

Ramp name	Rank	Number of trailers (mean ± SD)	Pearson *r*	Permuted *P*-value
Jena County boat ramp	4	28.67 ± 23.77	0.950	0.001
Spring Warrior boat ramp	12	7.88 ± 6.99	0.845	0.001
Hagen's Cove boat ramp	9	3.92 ± 4.33	0.838	0.001
Rocky Creek boat ramp	8	18.23 ± 19.37	0.833	0.001
Keaton Beach boat ramp	2	79.40 ± 56.46	0.808	0.001
Deakle Beach boat ramp	15	1.17 ± 1.47	0.779	0.003
Horseshoe Beach boat ramp	3	28.97 ± 21.69	0.777	0.003
Suwanee boat ramp	19	16.73 ± 8.94	0.723	0.003
Good Times Marina, entering	6		0.721	0.122
Dallus Creek boat ramp	11	2.77 ± 2.68	0.714	0.004
Jena County boat ramp, exiting	4		0.703	0.014
Steinhatchee boat ramp	1	108.10 ± 78.48	0.681	0.007
River Haven Marina, exiting	7		0.665	0.017
Yates Creek boat ramp	14	3.46 ± 2.60	0.640	0.027
Jena County boat ramp, entering	4		0.626	0.040
Fenholloway River boat ramp	18	0.62 ± 0.96	0.595	0.026
River Haven Marina, entering	7		0.565	0.065
Fenholloway boat ramp	20	2.57 ± 1.99	0.554	0.051
Dark Island boat ramp	10	6.46 ± 5.74	0.521	0.062
Sea Hag Marina, exiting	5		0.438	0.062
Sand Ridge boat ramp	13	0.43 ± 0.94	0.418	0.163
Good Times Marina, exiting	6		0.417	0.376
Jabo boat ramp	16	0.27 ± 0.47	0.358	0.283
Sea Hag Marina, entering	5		0.263	0.281
Spring Creek boat ramp	17	0.23 ± 0.60	0.177	0.596

TABLE 5. Results of Akaike information criterion (AIC) model selection of the optimal subset of variables for the number of bay scallops per vessel (CPUE), the number of vessels, and the proportion of vessels scalloping. The following values are provided for each optimal variable: residual sum of squares (RSS), the coefficient of multiple determination (R^2), R^2 adjusted for the number of predictors and sample size (R^2 adj), the corrected value of AIC for the model, AIC weights (Wts), and DeltaN, which provides a comparison to the best model. Season date was selected as an optimal variable in all models. In the scallops-per-vessel model, ordinated turbidity was also selected as an optimal variable. In the number-of-vessels model, day of the week was additionally selected.

Model	Variable	RSS	R^2	R^2 adj	AIC	Wts	DeltaN
Scallops/vessel	Season date	1.997	0.468	0.448	−73.136	0.954	15.984
	Turbidity	1.521	0.595	0.564	−78.534	0.625	5.397
	None	1.521			−78.534	0.158	0.000
Vessels	Season date	2.510	0.154	0.123	−66.497	0.266	2.550
	Day of the week	2.138	0.280	0.224	−68.649	0.297	2.152
	None	2.138			−68.649	0.180	0.000
Proportion scalloping	Season date	0.233	0.557	0.541	−135.433	0.999	21.295
	None	0.233			−135.433	0.126	0.000

decline throughout the season, with an abrupt decline during August, likely due to an increase in turbidity that month ($R^2 = 0.75$, $F = 41.62$, $P = 0.001$; Figure 5). The model of CPUE indicates that, on average, most harvesters collected less than their limit. The difference between harvest limit and actual harvest was relatively consistent, though it was larger in August (Figure 5). The number of vessels on the water also decreased throughout

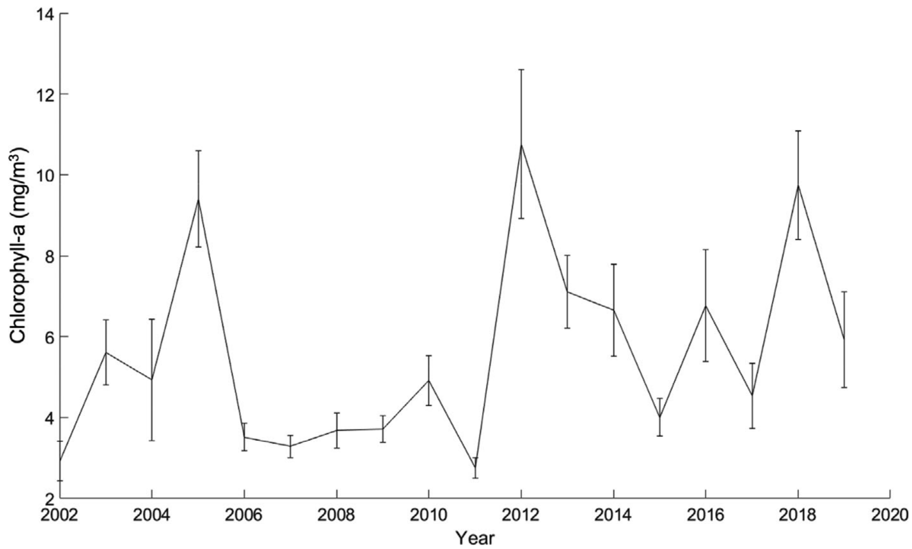

FIGURE 4. Annual average (error bars show 95% CIs) levels of chlorophyll *a* (mg/m^3) during the bay scallop harvest season (June 16–September 10) from 2002 to 2019.

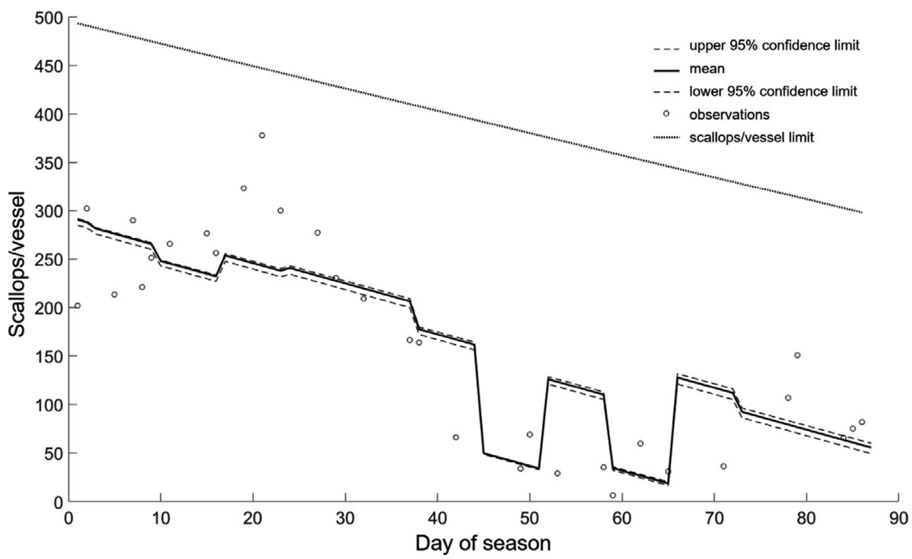

FIGURE 5. The model of CPUE in terms of the number of bay scallops per vessel (S_V) throughout the scallop season is given by the following equation: $S_V = -26.842T_U - 2.636D + 269.428$, where T_U is ordinated turbidity and D is the day of the season. The harvest limit of bay scallops per vessel throughout the season is shown for comparison.

the season, but it increased markedly on Fridays and Saturdays, which accounts for the peaks in the model ($R^2 = 0.47$, $F = 12.40$, $P = 0.001$; Figure 6). Finally, the proportion of vessels (P_r) harvesting bay scallops decreased linearly throughout the season ($R^2 = 0.65$, $F = 54.46$, $P = 0.001$) as $P_r = -0.52D + 83.12$.

Based on the models of total vessels and the proportion of those vessels harvesting bay scallops, an estimated 21,579 (95% CI = 20,621–24,535) vessels harvested bay scallops in the zone during the season. Incorporating the model of the number of harvesters on a vessel provides an estimate of 82,398 people (95% CI = 78,739–93,693) who engaged in harvesting bay scallops in the zone. Combining the models of total vessels, proportion of vessels harvesting bay scallops, and number of bay scallops harvested per vessel provides us with an estimated 4.24 million (95% CI = 3.92–4.91 million; Figure 7) bay scallops harvested during the season. The number of bay scallops harvested also decreased throughout the season; it was lowest in August, likely due to increased turbidity.

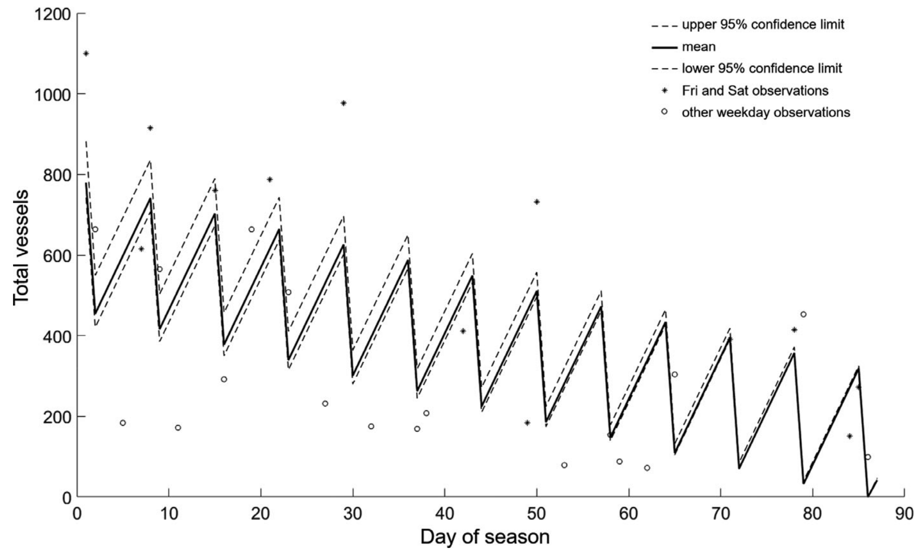

FIGURE 6. The model of the total number of vessels on the water in the study area throughout the harvest season is given by the following equation: $V = 53.189W - 5.485D + 412.400$, where W is the day of the week and D is the day of the season ($R^2 = 0.75$, $F = 41.62$, $P = 0.001$). Observations made on Fridays and Saturdays are differentiated from those made on other days of the week because the number of vessels varies significantly among days of the week.

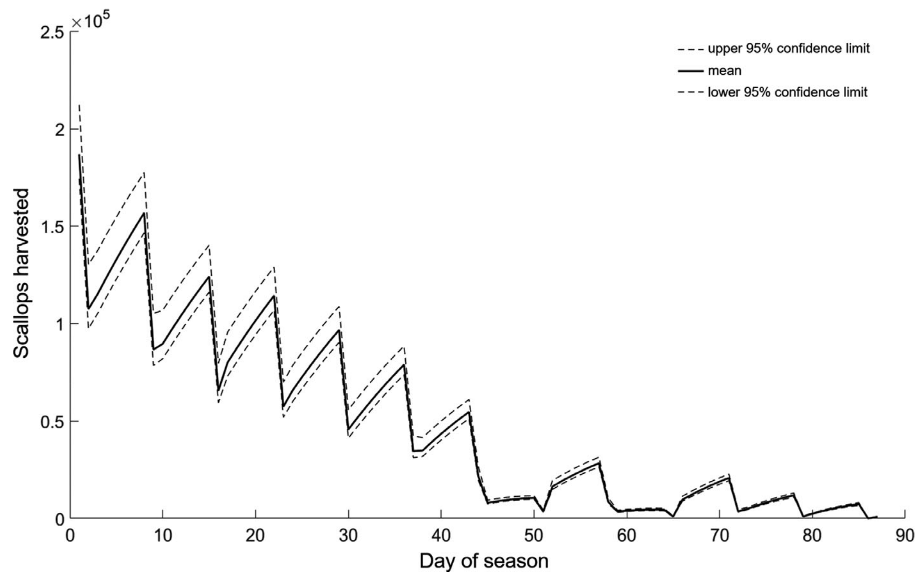

FIGURE 7. The number of bay scallops harvested throughout the scallop season in the study area was calculated by multiplying the CPUE in terms of bay scallops per vessel (S_V) by the number of vessels and the proportion of vessels harvesting scallops ($R^2 = 0.47$, $F = 12.40$, $P = 0.001$). Bay scallop harvest declines throughout the season and totals 4.24 million bay scallops (95% CI = 3.92–4.91 million).

Combining Fishery-Independent and Fishery-Dependent Results

The preseason diver survey recorded an average density of 0.0994 scallops/m^2 (95% CI = 0.0769–0.1219). Interpolating that density with ArcGIS to the surveyed area of approximately 105 km^2 resulted in an estimated preseason abundance of 9.38 million bay scallops (Table 6). In comparison, the postseason average density was 0.0285 scallops/m^2 (0.0223–0.0347), and the estimated postseason abundance was 2.53 million bay scallops (Table 6). Historical surveys conducted by the FWRI (unpublished data) estimate pre- and postseason bay scallop density for the Steinhatchee zone at 0.1127 scallops/m^2 (95% CI = 0.0796–0.1459) during preseason surveys and 0.0591

TABLE 6. Bay scallop harvest, population size, and mortality within the survey area and scalloping grounds. Upper and lower 95% confidence limits (CLs) are not provided for estimates of initial population size because these were obtained from an interpolation of densities in ArcGIS, which does not provide an error estimate. Final population size (N_t), seasonal total mortality (A), and instantaneous total mortality (Z) are calculated using initial population size and do not have associated error estimates.

	Survey area			Scalloping grounds		
Variable	Lower 95% CL	Mean	Upper 95% CL	Lower 95% CL	Mean	Upper 95% CL
C: Bay scallop harvest (millions)	3.920	4.242	4.907	3.920	4.242	4.907
N_0: Initial population size (millions)		9.380			1.230	
N_t: Final population size (millions)		2.528			3.356	
A: Seasonal total mortality		0.7305			0.7272	
u: Seasonal fishing mortality	0.4180	0.4522	0.5232	0.3187	0.3449	0.3990
v: Seasonal natural mortality	0.3126	0.2783	0.2074	0.4084	0.3823	0.3282
Z: Instantaneous total mortality		0.0151			0.0149	
F: Instantaneous fishing mortality	0.0086	0.0093	0.0108	0.0065	0.0071	0.0082
M: Instantaneous natural mortality	0.0064	0.0057	0.0043	0.0084	0.0078	0.0067

scallops/m^2 (0.0243–0.0952) during postseason surveys. Thus, the pre- and postseason densities in Steinhatchee in 2018 overlapped the historical averages for that area.

Creel surveys revealed that the surveyed area was heavily used for the harvest of bay scallops but also that additional harvest occurred north and south of the surveyed area (Figure 2). The total area in which the harvest was heaviest (i.e., the scalloping grounds) encompassed an additional 44 km^2 (Figure 2). Given that no diver surveys were conducted in these additional areas, we extrapolated average densities to estimate bay scallop abundance for the scalloping grounds, which encompassed a total of 149 km^2. Thus, estimated preseason abundance on the scalloping grounds was 12.30 million bay scallops, and estimated postseason abundance was 3.36 million bay scallops (Figure 2; Table 6).

Average shell height measured during preseason diver surveys was 48.54 mm (95% CI = 48.29–48.79) and that measured during postseason diver surveys was 56.86 mm (56.52–57.20). In comparison, average shell height, as determined from images of bay scallops from the creel surveys, was 51.06 mm (50.66–51.47) at the start of the season and 59.27 mm (58.78–59.76) at the end of the season. Shell height from the creel surveys was significantly greater than that from the diver surveys at both the beginning (t = −8.739, $P = 0.001$) and the end of the season (t = −6.197, $P = 0.001$).

Seasonal total mortality (A) in the surveyed area was 0.7305, with fishing mortality measured at 0.4522 (95% CI = 0.4180–0.5232) and natural mortality at 0.2783 (0.2074–0.3126; Table 6). The value of daily instantaneous total mortality was 0.0151 for the surveyed area, with values of F ranging from 0.0086 to 0.0108 and values of M ranging from 0.0043 to 0.0064 (Table 6). While seasonal fishing mortality was higher than seasonal natural mortality in the surveyed area, the reverse was true on the scalloping grounds. (Table 6).

Surveys conducted by the FWRI (unpublished data) from 1994 to 2017 in areas outside of the Steinhatchee zone, including areas open and closed to harvest, were used to calculate historical mortality in these areas. Excluding surveys that recorded either no mortality or 100% mortality over the course of a season, 78 surveys were conducted, 43 in areas open to harvest and 35 in closed areas. In areas closed to harvest, total seasonal mortality ranged from 6.3% to 97.6% (mean ± SD = 56.2 ± 28.7%), while in open areas the range increased from 3.8% to 99.4% (55.7 ± 29.7%). For surveys conducted in the Steinhatchee zone only, mortality was slightly higher and ranged from 12.7% to 96.7%, with a mean ± SD of 66.6 ± 22.5%. Thus, the estimate of mortality (73.1%) for the Steinhatchee zone in 2018 is within the range for these zones and within the average range for the Steinhatchee zone.

The modified Leslie–Delury analysis revealed a significant relationship between cumulative catch (K_t) and CPUE (C_t/f_t) ($R^2 = 0.711$, $F = 204.32$, $P = 0.001$; Figure 8). The slope of the relationship between K_t and C_t/f_t, given as q' in the modified Leslie–DeLury analysis, was 1.236×10^{-4}. Instantaneous natural mortality from the surveyed area ($M = 0.0057$) was used to calculate the catchability coefficient (q) as 3.19×10^{-5} (95% CI $= 2.74 \times 10^{-5}$ to 3.85×10^{-5}). The initial population size (N_0) was calculated using the modified Leslie–DeLury analysis as 11.03 million bay scallops (95% CI = 9.16–12.88 million). This initial population size was not significantly different from that calculated from the fishery-independent diver surveys

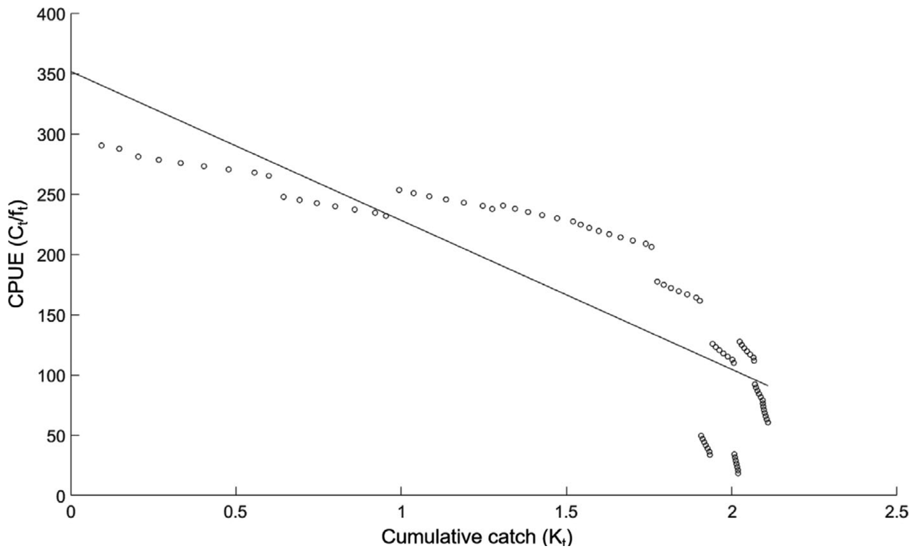

FIGURE 8. The modified Leslie–DeLury analysis of cumulative catch shows that there is a significant relationship between cumulative catch (K_t) and CPUE (C_t/f_t) in the form of $C_t/f_t = 1.236 \times 10^{-4} K_t + 351.705$ ($R^2 = 0.711$, $F = 204.32$, $P = 0.001$).

(9.38 million) because the value was within the 95% confidence limits.

Simulations

In the management strategy evaluations, the normal scenario (Table 7; Figure 9) represents the actual season length and harvest effort measured in this study. The estimates of mortality for the normal scenario are slightly different from those in Table 6 because the normal scenario was extended to end on September 25 for comparison to the other scenarios. Although mortality due to fishing ends on September 10 in the normal scenario, natural mortality occurs through September 25. Scenarios 1 through 3 resulted in similar final population sizes that were all within 1–2% of the population size from the normal scenario, but the lowest population size resulted from starting the season on July 1 and increasing season length by 2 weeks (scenario 2). Extending the season by an additional 2 weeks (scenario 1) reduced the final population size by only 0.80%. Shortening the season by starting it on July 1 (scenario 3) increased the final population size by only 1.49% over the normal scenario. In comparison, limiting the season to 1 month (scenario 4) increased the final population size by 24.58%.

In the scenario altering harvest effort, reducing the harvest regulation limit to 1 gallon per person for the first 2 weeks of the season resulted in a final population increase of 11.70% (scenario 5). Interestingly, a permanent reduction in the legal harvest by one-half resulted in a reduction of the final population size by 5.18% (scenario 6). In scenario 7, in which all harvesters on a vessel collect their regulation limit, the bay scallop population in the survey

TABLE 7. Estimates of mortality, harvest, and population size for the 10 management scenarios evaluated. See Table 2 for descriptions of the 10 scenarios and Table 6 for definitions of the variables listed here.

	Scenarios										
Variable	Normal	1	2	3	4	5	6	7	8	9	10
C (millions)	4.220	4.242	3.925	3.846	3.086	4.049	4.585	9.169	8.203	6.605	1.211
N_0 (millions)	9.380	9.380	9.380	9.380	9.380	9.380	9.380	9.380	9.380	7.542	1.382
N_t (millions)	2.549	2.529	2.513	2.588	3.380	2.887	2.417	0	0	0	0
A	0.7282	0.7304	0.7321	0.7241	0.6396	0.6922	0.7423	1.0000	1.0000	1.0000	1.0000
u	0.4040	0.4073	0.4097	0.3980	0.2762	0.3515	0.4248	0.9580	0.9580	0.9580	0.9580
v	0.3242	0.3231	0.3224	0.3261	0.3635	0.3407	0.3175	0.0420	0.0420	0.0420	0.0420
Z	0.0129	0.0130	0.0130	0.0127	0.0101	0.0117	0.0134	0.1368	0.1368	0.1368	0.1368
F	0.0072	0.0072	0.0073	0.0070	0.0044	0.0059	0.0077	0.1310	0.1310	0.1310	0.1310
M	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057	0.0057

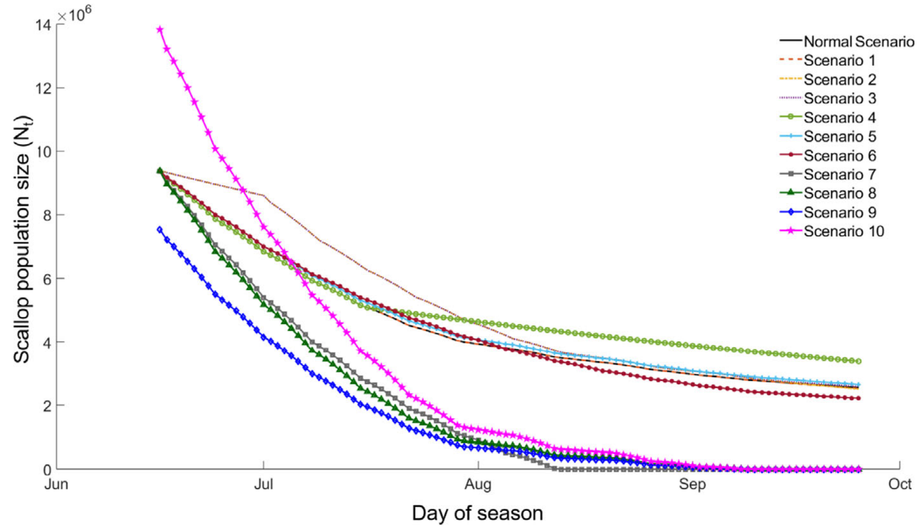

FIGURE 9. Simulations of bay scallop population size (N_t) from June 16 to September 25, 2018, under 10 management scenarios (as described in Table 2).

area would be extirpated after 58 d. Increasing by 1.94 times the number of vessels harvesting bay scallops would extirpate the bay scallop population in the survey area by the end of an otherwise normal season (scenario 8). For a historically low starting population size (scenario 9), effort would need to increase by only 1.57 times to eradicate the population, while effort would need to increase by 2.87 times to extirpate a historically high starting population size (scenario 10; Table 7; Figure 9).

DISCUSSION

Bay Scallop Fishery and Harvester Characteristics

This is the first comprehensive study using a combination of both fishery-independent and fishery-dependent methods to evaluate the recreational harvest of bay scallops in Florida. The recreational fishery in a management zone centered in Steinhatchee appears to function as a derby-style fishery, with a tremendous amount of effort occurring when the season opens, followed by a steady decline for the remainder of the season. Harvest effort was not significantly affected by weather conditions (precipitation, presence of lightning, wind speed, and many other variables) nor were conditions useful in predicting effort. The only environmental variable that appeared to negatively affect harvest effort was increased turbidity because harvesters mostly snorkel to collect bay scallops. Turbidity in 2018 was unusually high in this area during August and might have reduced our catch estimate compared with more typical years.

The regulations for the recreational bay scallop fishery specify harvest limits in terms of gallons of whole bay scallops or pints of meat. Yet only 2% of harvesters reported their catch to creel samplers in pints of meat. Furthermore, harvesters who reported their catch in pints frequently used Ziploc bags to store their catch and were uncertain of the number of pints they had collected. In this study, we assumed that 2 gallons of whole bay scallops was equivalent to 1 pint of adductor meat, but Geiger et al. (2006) showed that the number of whole bay scallops in 2 gallons is significantly less than the number of bay scallops constituting 1 pint of meat in September in Steinhatchee. Considering that only a small fraction of harvesters shuck bay scallops on the water and given the uncertainty associated with using this measurement, basing a harvest restriction on pints of meat is questionable.

Although most harvesters reported their catch in terms of gallons of bay scallops (74%), the number of gallons collected was often estimated by the creel samplers. Many harvesters had placed their catch in a cooler with ice, making it difficult for harvesters or creel samplers to verify the number of gallons harvested. Additionally, many harvesters expressed confusion as to how to evaluate their catch in terms of gallons. A campaign designed to educate harvesters on how to measure their harvest (e.g., using demarcated buckets), or a harvest limit in terms of the number of whole bay scallops, might alleviate this confusion. Average bay scallop size during the pre- and postseason surveys revealed that harvesters were collecting larger-than-average bay scallops. Because most harvesters are relatively inefficient at harvesting bay scallops, collecting only approximately 22% of available bay scallops in an area, it makes sense that they would tend to collect larger bay scallops, which are easier to find.

The recreational bay scallop fishery in Steinhatchee attracted people from nearly every county in Florida and

16 other states. A relatively large proportion of harvesters originated from Georgia (14%). Hall-Scharf et al. (2018) estimated that recreational bay scallop harvesters in Hernando County spent US$84 per vessel per day in 2017 on fuel, supplies, fees, and lodging. An estimated 21,579 vessels harvested bay scallops in Steinhatchee in 2018, and if we assume that each vessel spent $84, total expenditures by harvesters would have been $1.81 million, which is approximately twice the amount spent in Hernando County in 2017 ($805,476). Approximately 32% of the trips in Hernando County originated in that county (Hall-Scharf et al. 2018), while only 9% of trips in the Steinhatchee zone originated from the counties in that zone (Taylor and Dixie counties).

Estimates of Mortality

Overall, it appears that fishing effort and fishing mortality have increased in the Steinhatchee zone since they were last measured in 2002. Total mortality of bay scallops during the season was 73.1%; fishing mortality accounted for 43.8% to 71.6% of total mortality, depending on the size of the area evaluated, with higher fishing mortality in the surveyed area than in the scalloping grounds. Greenawalt-Boswell et al. (2007) evaluated fishing and natural mortality for the recreational bay scallop fishery in Florida using aerial surveys to estimate harvest effort and diver surveys to evaluate bay scallop densities. The authors conducted the study in 2002 over a 57-km^2 area in the Steinhatchee area and estimated total seasonal mortality at 84.7%, of which fishing mortality accounted for 19.7%. To gauge harvest, the authors assumed that every vessel that fished collected 8 gallons, or 400 bay scallops, for an estimated total harvest of approximately 2.05 million bay scallops. The initial bay scallop density in Steinhatchee in 2002 was higher than that measured in 2018 (0.231 scallops/m^2 versus 0.099 scallops/m^2), which may partly explain the lower fishing mortality estimated in 2002. Additionally, the 2002 initial population, estimated at 12.3 million over 57 km^2, may be an overestimate, considering that it is equivalent to the population estimated in 2018 for an area of 149 km^2. Furthermore, harvest effort may have increased from 2002 to 2018 since fewer vessels on average were observed on weekends and weekdays in 2002 than in the present study (weekdays: 20 versus 277; weekends: 188 versus 516).

In a mark–recapture study in St. Joseph Bay, Bologna (1998) found that instantaneous natural mortality (M) in bay scallops ranged from 0.006 to 0.042, higher than the range observed in the present study (0.004–0.008). Converting M from Bologna (1998) to seasonal total mortality (A) for an 87-d season results in values ranging from 39.1% to 97.4%, which includes the value of total mortality estimated here (73.1%). Yet estimates of mortality from Bologna (1998) may have been biased because they took into account emigration and a mass-mortality event that occurred during the study.

Estimates of Population Size

The density of bay scallops measured in this study was 0.099 scallops/m^2, although the historical average for the Steinhatchee area is 0.113 scallops/m^2. In comparison, following intensive restoration efforts, the density of adult bay scallops in the Peconic Bay of New York increased to an average of 0.068 scallops/m^2 that corresponded to an increase in commercial landings of bay scallops in the area (Tettelbach et al. 2015). Although Peconic Bay and Steinhatchee support similar bay scallop densities, the Peconic Bay is open to both the recreational and commercial harvest of bay scallops. Harvest regulations on bay scallops in New York limit collections to only those bay scallops that have already spawned once by setting the harvest season from November to March and only permitting the collection of bay scallops with a well-defined growth ring (https://www.dec.ny.gov/outdoor/29870.html). Thus, these harvest limits may preserve the spawner population and enable the Peconic Bay, with roughly equivalent scallop densities as Steinhatchee, to support both recreational and commercial fisheries.

A weakness of the present study is that the fished area (i.e., the scalloping grounds) was approximately 50 km^2 larger than the area surveyed by divers in the evaluation of population size. During the 2019 preseason surveys, we conducted additional surveys in the northern portion of the scalloping grounds to evaluate the area that was not surveyed in 2018. We found that bay scallop density in the northern portion of the scalloping grounds was approximately 40% of that in the southern portion surveyed in 2019 (unpublished data). Extrapolating average density from the surveyed area in 2018 to the extent of the scalloping grounds may well have overestimated population size there and caused an overestimate of natural mortality there as well. Therefore, the estimates of fishing and natural mortality for the surveyed area are likely more accurate, with fishing mortality accounting for 57.5–71.6% of seasonal mortality.

A meta-analysis of exploitation intensities on spawning stock biomass in fisheries for small pelagic fishes suggested that exploitation rates ($E = F/Z$) greater than 0.4 ($F = 2/3{\cdot}M$) are associated with stock declines and that rates less than 0.4 are associated with stock recovery (Patterson 1992). Exploited pelagic fisheries function similarly to the bay scallop fishery in that pelagic stocks are relatively short-lived and subject to high natural mortality. The exploitation rate of the bay scallop fishery in the surveyed area ranged from 0.57 to 0.72, suggesting that this fishery cannot sustain itself under that intensity of harvest. Thus, further monitoring of the fishery is warranted to determine whether the fishing mortality measured in this study is typical and constant for this zone. Bay scallop population size was interpolated to the extent of the 1.83-m depth contour in this study because the survey design was limited to depths shallower than 1.83 m. This study design was modeled after surveys of the bay scallop population in Florida that the FWRI has conducted since 1994. While total population size may have been underestimated in this study by excluding seagrass habitat deeper than 1.83 m, it is likely that the population size subject to harvest was estimated correctly because both fishery-independent and fishery-dependent estimates of initial population size were in agreement. Because scallop harvesters appear to focus their effort on bay scallops in relatively shallow water, future studies should investigate whether bay scallops in deeper waters may act as a refuge spawning stock that may sustain the overall population.

The modified Leslie–DeLury model used in this study assumes a closed population; thus, recruitment, immigration, or emigration would introduce errors into the abundance estimate. While immigration into or emigration of adults out of the zone is not likely for this species given its limited observed movement (Barber and Blake 1983), recruitment has been observed at low levels in a nearby estuary in summer (Geiger et al. 2010). Additionally, the modified Leslie–DeLury model assumes that catchability is consistent across the fishery and that CPUE will decline in proportion to abundance; thus, any uncertainty in catch rates may underestimate catchability and overestimate initial biomass (Ricker 1975). Despite its assumptions, however, this model produced an estimate of initial population size that was not significantly different from those derived from fishery-independent methods for both the surveyed area and the scalloping grounds. Thus, it appears that the fishery-dependent methods used in this study provided a reliable estimate of catch rates and the bay scallop population in this management zone.

Management Strategy Evaluations

Although the management strategy evaluations considered only 1 year of data, bay scallop densities for 2018 fall within the averages estimated in earlier studies for preseason and postseason bay scallop densities, and the harvest may be conservative due to the atypically high turbidity experienced during the 2018 season. Simulations altering season length and timing revealed that minor alterations would have a negligible impact on the bay scallop population. The present season start date of June 16 for the zone results in a reduction of the final population of 1.42% less than the final population under scenario 2, in which the season starts on July 1. Therefore, it appears that recent management actions adjusting the season start date within the June 16 to July 1 period in this zone have had a minor impact on the bay scallop population there.

Small changes to the start date did not appear to substantially impact the final population, but these simulations do not consider the impact to the spawning population. Bay scallops in the Steinhatchee zone reach a peak in gonadosomatic index in August and September (Geiger et al. 2006), suggesting that spawning may occur during or shortly after the open season. Thus, the season in this zone opens before most bay scallops are likely to have spawned, and opening the season after spawning is likely to have occurred in the fall would clearly increase the sustainability of this fishery in this zone. Future studies of management scenarios in the zone should focus on dates that would ensure a sustainable spawning stock biomass after the season.

We found that the more recent management action taken in 2020 of reducing the harvest limit to 1 gallon per person early in the season (June 16–July 1) had a greater impact on the 2018 population estimate, increasing the final population size by 11.70%. This finding is likely due to the smaller count of bay scallops early in the season and the derby nature of the fishery. Surprisingly, reducing the harvest limit by half throughout the season resulted in only a slightly decreased final population size. The reason is that harvests later in the season were often well below half of the harvest limit so assuming that harvesters collected half the limit throughout the season increased the overall harvest.

Assuming that all harvesters collect the legal limit of bay scallops is likely unrealistic, but given that the population in the model was extirpated after 58 d, it reveals that the population in the Steinhatchee zone may not be able to sustain the current maximum legal harvest limits if CPUE, number of participants, or catchability were to increase. Harvesters and novice snorkelers collected an average of approximately 22 bay scallops per hour at the beginning of the season. The novice snorkelers missed approximately 78% of the available bay scallops on a transect, and presumably the harvesters missed the same amount. The catchability coefficient further confirms the relatively low efficiency of harvesters, as it was estimated that each vessel caught only 0.012% of the bay scallop stock. Therefore, the relatively low efficiency of harvesters may contribute more to the preservation of the population in this zone than the present harvest regulations.

A more realistic scenario is an increase in the number of vessels harvesting bay scallops. In fact, the number of vessels observed by Greenawalt-Boswell et al. (2007) in 2002 had increased by more than an order of magnitude by 2018, as observed in this study. Yet in this study, just a doubling of harvest effort would extirpate the population by the end of the season, despite the relatively low efficiency of harvesters. In a year with the lowest recorded bay scallop population size, an increase in effort of only 1.57 times would extirpate the population, while even in a year with the highest population size, effort would need to increase by only 2.87 times to wipe out the local population (scenario 9). Spawning likely occurs at the end of and after the season, so if the population were extirpated by the end of the season, it very well might collapse without the supply of larvae from other populations. Yet, as bay scallop abundance declines it is also likely that fishing effort would decline, which may not result in the extirpation of the local bay scallop population.

Future Studies

Boat ramps that experienced the heaviest use, and thus were targeted for creel surveys, were not always the ramps most highly correlated with the number of vessels on the water. For instance, Spring Warrior Fish Camp boat ramp had the highest correlation of trailers to vessels ($r = 0.845$) after Jena County boat ramp ($r = 0.950$), despite having nearly one-third as many trailers at the ramp, on average. Therefore, future efforts to use trailer counts to estimate vessel counts should not necessarily target the most heavily used ramps for this purpose. The number of vessels entering and exiting the Steinhatchee River from the vantage point provided at the Jena County boat ramp was correlated with vessel counts, but this correlation was weaker than boat ramp trailer counts. Thus, future efforts to estimate the number of vessels on the water harvesting bay scallops should focus on boat ramp trailer counts because they are both more efficient and accurate. In addition, future efforts to conduct vessel counts should evaluate whether double counting of vessels occurs.

Due to the derby nature of the fishery, future efforts to monitor harvest should focus, at the very least, on sampling at the beginning and the end of the season. Furthermore, sampling should include both weekends and weekdays, and especially Fridays and Saturdays, because the day of the week was a significant variable in the harvest model. The number of trailers at boat ramps peaked between 1000 and 1300 hours, so future aerial surveys and boat ramp trailer counts should focus on sampling during that time frame. Correspondingly, creel sampling should be conducted between 1300 and 1600 hours, which would maximize the number of interviews conducted.

Conclusions

The comparison of recreational fishery harvest to fishery-independent estimates of bay scallop abundance in the management zone centered at Steinhatchee in 2018 revealed that the model used here is informative for testing current and future management scenarios in this valuable state fishery. Increasing seasonal fishing mortality in the Steinhatchee zone over the past 16 years is a trend that should be monitored because if fishing effort increased to twice that in 2018, the fishery would be in danger of collapsing. The lack of a target spawning stock biomass for management of this fishery is a concern. The present exploitation rate of the bay scallop fishery in the zone studied exceeds 0.4, which suggests that this fishery may be unable to sustain itself. Our analysis of recent changes in season length and start dates suggests that they have had a relatively minor impact on the overall fishery. With an estimated 82,398 people participating in this zone in 2018 and the estimated $1.81 million in revenue generated for this economically depressed zone, there is a financial incentive for even further expansion of the fishery there. Continued monitoring of harvest effort in this zone is therefore recommended, and managers probably should consider changing harvest limits if harvest effort continues to increase.

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