1 **Examining the performance of alternative harvest regulations for short-lived**

2 **taxa; a case study of Florida Bay Scallop Management**

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20   **Highlights**

21   • Recreational fisheries for annual species are not often evaluated quantitatively

22   • Harvest regulations that are matched to life history can improve expected outcomes

23   • A later harvest season or a "rolling" bag limit would benefit this scallop fishery

24   • Rolling bag limits mirror escapement policies like those in commercial fisheries

Abstract

The life history schedule of short-lived species compresses the temporal window available for harvest and exacerbates harvest timing decisions. For annual species whose populations are made up of a single year class, it is challenging yet essential to limit harvest to a level that will allow sufficient spawning escapement to sustain the population. Unexpectedly, intense harvest prior to reproduction could extirpate a population in a single season. Larger-scale commercial fisheries for annual or semelparous species are often managed using sophisticated pre-season abundance forecasts or in-season depletion estimates combined with intensive monitoring of catches and enforcement of catch limits. However, sufficient monitoring and harvest control are rarely feasible in recreational fisheries. We demonstrate the use of an age-structured simulation model to identify robust management regulations for recreational harvest season and bag limits applied to the Florida bay scallop fishery. We compared the outcomes of current harvest regulations with a suite of alternative harvest regulations in a recreational fishery for Florida bay scallops. To account for uncertainty in the stock status and dynamics of the fishery, we evaluated alternative harvest options across three levels of initial stock exploitation and two scenarios for future fishing effort. Our results show that biologically-informed regulations, which allowed for more bay scallops to spawn prior to harvest, such as a later harvest season and daily harvest limit increasing over the season, performed well across all treatments, and outperformed many of the current regulations when the initial stock state was more exploited, as well as when future effort doubled. These results suggest that (1) harvest regulations that more closely match the biology and life history are likely to perform better for short-lived, annual taxa than simpler regulations that may not explicitly consider these factors, and (2) simpler regulations can perform well, but

47   require precise, annual monitoring to prevent potentially catastrophic overharvest or costly

48   underutilization.

49   **Keywords**: *Argopecten irradians concentricus*, recreational fisheries, harvest season, bag limits,

50   population simulation

1. Introduction

Fisheries for short-lived or annual species pose challenges for harvest management. Annual species have a simpler (single mode) size structure and truncated age structure compared to most managed fish species. This compression of age and size structure as a function of comprising but a single year class means that these species are highly sensitive to effects of human exploitation. Larger-scale commercial fisheries for such species are often managed using sophisticated pre-season abundance forecasts or in-season depletion estimates (e.g., Rosenberg et al., 1990; Arkhipkin et al., 2015) combined with intensive monitoring of catches and enforcement of catch limits to ensure sufficient spawning escapement. Although recreational fisheries for short-lived species are common and socioeconomically important (Lellis-Dibble et al., 2008; Taylor, 2017; Aguilera, 2018; Ben-Hasan, 2018; Sydeman et al., 2020), these fisheries are more difficult to monitor, assess, and manage than major commercial fisheries. The large, unrestricted pool of potential recreational fishers entering from numerous access points along with limited traditional means of restricting catch (such as using season, length, or bag limits) constrain the available means to manage recreational fisheries for short-lived or annual species.

Precision is necessary for the amount and timing of harvest for short-lived species with essentially a single age or size class, e.g., small-bodied fish, some crabs, many shrimp, and many cephalopods (Robert et al., 2010; Arkhipkin et al., 2015; Sauer et al., 2021; Žák et al., 2021). Most traditional fisheries models were developed for longer-lived fish and invertebrate species because these models assume the existence of multiple year classes and population dynamics associated with iteroparity (Arkhipkin et al., 2021). Compression of age and size structure in annual species entails a meaningful proportion of the population need to spawn each year to ensure sustainable harvest as population replenishment and viability is highly dependent on

74   spawning success of a sole cohort (and not buffered by any carry-over of spawning stock year to

75   year; Rosenberg et al., 1990). However, harvesting also needs to occur before rapid post-spawn

76   senescence, which renders the organism unpalatable or undesirable to catch (notably occurs in

77   some semelparous species such as pacific salmon and octopus). Additionally, delaying harvest

78   until after their peak spawning period will likely decrease overall socioeconomic utility as most

79   of the stock would succumb to natural mortality without being harvested. Conversely, high

80   fishing mortality rates before most of the spawning has occurred, in addition to the potential for a

81   critical reduction in spawning potential, could result in growth overfishing that would undercut

82   harvestable biomass.

83   Common harvest regulations in recreational fisheries include season length and bag

84   limits. Effects of season timing and length may interact with bag limits (Melnychuk et al., 2021);

85   liberal bag limits may especially function to "shorten" the season by quickly removing the

86   available stock, whereas very conservative bag limits may constrain harvest-based utility.

87   However, there are very few studies quantitatively evaluating the biological sustainability and

88   harvest utility tradeoffs resulting from the more unique aspects of these annual species life-

89   histories.

90   Most research on fisheries for such species has focused on commercial take (Rosenberg

91   et al., 1990; Hoshino et al., 2012; Ben-Hasan et al., 2018), with fewer studies evaluating

92   recreational fisheries (Reid and Montgomery, 2005), and very few evaluating the harvest season

93   and bag limit regulations that are important to sustaining the socioecological system of these

94   fisheries (Forbes et al., 2019). Among the reasons for this is the large number of active and

95   potential participants in recreational fisheries given essentially unrestricted access (fishing

96   licenses are required but are cheap and their number is not limited) and the dispersed nature of

97   access points which make monitoring difficult and unprecise while also limiting the ability of

98   mangers to effectively constrain harvest. Typically, such fisheries are harvest-oriented and cease

99   outside of the harvest season (e.g., Taylor et al., 2017; Ben-Hasan et al., 2018; Arkhipkin et al.,

100 2022), but while participating, fishers attain utility from both catch-related and non-catch-related

101 attributes of the fishing experience. Popular recreational fisheries of these species also support

102 economically important visitation and tourism activities, and thus are vital to local communities.

103 The extent to which local economies depend on these fisheries emphasizes the importance of

104 setting appropriate season and bag limits. Shorter seasons will limit annual market activity, but a

105 single year of overly intense harvest from lenient season lengths and bag limits could collapse

106 the entire fishery. Successful local governance requires evaluations of social and ecological

107 dynamics to set reasonable and sustainable regulations.

108   Here we consider a case study of a recreational fishery for a short-lived species that has

109 high socioeconomic value locally: the bay scallop (*Argopecten irradians concentricus*) fisheries

110 of the Gulf coast of Florida, USA. Many different types of regulations have been adopted across

111 counties, but little management evaluation exists to determine which of these regulations

112 optimize ecological and socioeconomic sustainability. The goals of this work are to evaluate

113 current and alternative management strategies for managing this species and provide applicable

114 management advice to a local fishery. We address these goals by building upon the initial

115 empirical work done by Granneman et al. (2021), developing a simulation model representing a

116 local Florida bay scallop fishery, and discussing the implications our results have for trade-offs

117 between current harvest regulations, like bag and season limits, and similar regulations tweaked

118 to be more biologically-informed by considering the life history schedule.

119 *1.1 Case Study*

120   Bay scallops are distributed from Massachusetts to Northern Mexico throughout the Gulf

121   and Atlantic coasts in the US, where they support commercial and recreational fisheries

122   (Mackenzie, 2008; Bert, 2011). The Florida bay scallop (*Argopecten irradians concentricus*) is a

123   subspecies currently found from St. Andrew Bay to Pine Island Sound along the Florida Gulf

124   coast (Geiger et. al., 2006). Florida bay scallops rarely live longer than 12-18 months (Barber

125   and Blake, 1983; Arnold et al., 2005) and spawn in late summer or early fall (Geiger et al.,

126   2010), however there is evidence of some protracted spawning throughout the year (Sastry,

127   1963; Geiger et al., 2010). This makes Florida bay scallops effectively an annual species and the

128   prevailing theory across the entire species range is that they reproduce usually only once, what

129   has been characterized as "interrupted iteroparity" since individuals may undergo multiple

130   spawning events however usually do not survive long enough for the second and senescence

131   does not appear to be directly related to spawning (Bricelj and Krause, 1992; Estabrooks, 2007;

132   Abele et al., 2009).

133   The fishery for bay scallops on the Gulf coast of Florida is exclusively recreational and

134   hand-harvest, with fishers swimming (usually snorkeling) over shallow sea grass flats and

135   locating scallops by sight. The species' occurrence in nearshore, shallow waters and the simple

136   harvest techniques has made the fishery especially popular with people who otherwise might not

137   engage in recreational fishing (Granneman et al., 2021). These traits also make the fishery a

138   social affair, with large, *ad-hoc* aggregations of scallop harvester vessels forming on the water,

139   and little indication of negative utility associated with crowding (as is common in other

140   recreational fisheries; Hunt et al., 2019). The popularity of this fishery attracts thousands of

141   visitors for day or overnight trips to coastal communities that rely on the additional revenue and

142   market activity (Hall-Scharf et al., 2018). Because the fishery is harvest oriented, essentially no

143   scalloping trips (and associated market activity) occur outside of harvest season. The fishery is

144   currently managed by bag limits (per individual and vessel per day) and by harvest seasons, but

145   the length and timing of the harvest season and bag limits are regulated differently in each of the

146   spatial management zones (Figure 1). While all harvest seasons occur generally during the

147   summer (and thus largely before or overlapping with scallop spawning), changes to the length of

148   the harvest seasons are perceived to have important implications for local economies (Hall-

149   Scharf et al., 2018). Despite this, quantitative assessments of harvest season efficacy and effect

150   on scallop population and socioeconomics are largely unexplored (Geiger et al., 2006;

151   Granneman et al., 2021).

152

153   **2. Methods**

154   *2.1 Approach*

155   We used a simulation approach to evaluate the effects of harvest regulations on bay

156   scallop population dynamics as well as metrics considered important to the socioeconomic utility

157   of scallopers. We developed an age structured simulation model for a hypothetical population of

158   bay scallops and subjected this population to alternative harvest regulations.

159   *2.2 Population model*

160   All analyses were conducted in R (R Core Team, 2022), and all data and code needed to

161   replicate our study are available from github.com/lidach/CampLabScallop. We built a single

162   area, single sex, age structured population model that simulates the monthly dynamics of a

163   hypothetical bay scallop fishery under different management actions. Where possible, we

164   parameterized the model using the most recent information from the literature (Table 1). We

165   chose a single sex model given bay scallops are functional hermaphrodites (Barber and Blake,

166 1985). We modeled bay scallop ages from 1 to 18 months, as 18 months is generally thought to

167 be the maximum age achieved in Florida (Barber and Blake, 1983). The model is initialized at an

168 unfished equilibrium age structure using:

169
$$(1) \quad N_{a,t=1} = \begin{cases} R_0 & if \ a = 1 \\ N_{a-1,t=1}e^{-M_{a-1}} & if \ a > 1 \end{cases}$$

170 where R_0 denotes unfished recruitment, M_a references the monthly instantaneous natural

171 mortality at age a, and t denotes the time step in months ($t = 1$ references the beginning of

172 model). Natural mortality was calculated using the length-inverse Lorenzen M, which assumes

173 that natural mortality declines with age until the maximum age of $a = 18$ months (T2.3;

174 Lorenzen, 2000, 2022). Upon reaching that maximum age, scallops are subject to infinite M, i.e.,

175 no scallops survive beyond $a = 18$ months. Shell height, measured from the hinge to the shell

176 margin, was calculated using the von Bertalanffy growth function (T2.1, Figure 2). We modeled

177 the weight at age of a scallop as a power function of shell height (T2.2), and the maturity-at-age

178 as a logistic function of age (T2.4).

179   The monthly scallop population simulates forward in time according to:

180
$$(2) \quad N_{a,t} = \begin{cases} R_t & if \ a = 1 \ and \ t = \text{every 12 months} \\ N_{a-1,t-1}e^{-(M_{a-1}+F_{a-1,t-1})} & if \ a > 1 \end{cases}$$

181 where $F_{a,t}$ represents the fishing mortality in a given month for a given age and R_t denotes

182 recruitment. Given the monthly time-step, spawning only takes place in select months

183 corresponding to the start of the year (every twelfth time step). Recruitment in each year (y) was

184 calculated deterministically using the Beverton and Holt function (Beverton and Holt, 1957):

185
$$(3) \quad R_t = \frac{\alpha S_{y-1}}{1 + \beta S_{y-1}} \quad if \ t = \text{every 12 months}$$

186   where $S_{y-1} = \sum_{t \ in \ y-1} \sum_{a} N_{a,t} * Mat_a * \psi_{month(t)} * \omega_a * Fec_a$

187   The accumulated spawning biomass for the year prior to recruitment, S_{y-1}, attempts to account

188   for the individuals that may have spawned prior to the 12th month in each year (December). This

189   quantity was calculated by summing the monthly spawning biomass produced by scallops within

190   a year (where the $\sum_{t \ in \ y-1}$ summation symbol denotes summation over a year). The vector ψ

191   denotes the probability of spawning in each month ($\psi_{month(t)}$, where *month(t)* references the

192   particular month depicted at time *t*), which accounts for the seasonality of spawning. This vector

193   was parameterized using relative values obtained from Figure 5 in Geiger et al. (2006), which

194   depicts the mean gonadal-somatic indices of bay scallops each month from the Homosassa area

195   of Florida's Gulf coast. The ability to spawn only once was enforced using ω_a, which describes

196   the proportion of individuals alive in a cohort at age *a* that are available to spawn (have not yet

197   spawned). This vector was derived according to

198      $\omega_a \begin{cases} 1 & if \ a = 1 \\ \omega_{a-1}\left(1 - Mat_{a-1} * \psi_{month(a-1)}\right) & if \ a > 1 \end{cases}$

199   where now *month(a-1)* references the specific month associated with age *a-1* in a cohort (e.g.,

200   age 1 and age 13 both reference January). For example, all individuals of age 1 are available to

201   spawn in January, since none spawned in the previous month. In February, the percentage of

202   individuals age 2 that are available to spawn is equal to the percentage of age 1s that were

203   available to spawn in the previous month multiplied by the percentage of age 1 individuals that

204   did not spawn in the previous month $\left(1 - Mat_{a-1} * \psi_{month(a-1)}\right)$. This assumes randomness with

205   respect to which scallops (spawned or not) died over the course of the year. We chose to assume

206   bay scallops were only able to spawn once in our model as the majority of the population in

11

207 Florida is assumed to (Barber and Blake, 1983), and the likelihood of surviving to a second

208 spawn is low (Estabrooks, 2007; Abele et al., 2009). The parameters α and β of the stock recruit

209 function were converted from the compensation ratio, CR (the relative improvement in juvenile

210 survival rate as the spawning stock biomass approaches zero, Goodyear, 1980), and the spawning

211 biomass produced per recruit in the unfished condition, ϕ_0 (T2.7-2.9). We assumed fecundity-at-

212 age was proportional to weight-at-age with an arbitrary scalar of 0.1.

213 *2.3 Fishery*

214   Fishing mortality per month is calculated as:

215   (4) $F_{a,t} = s_a q E_t$

216 where s_a denotes the fishery selectivity of scallops at age, q the catchability of scallops in the

217 fishery, and E_t the effort expended in each month, measured as the number of scallopers. The

218 fishery selectivity of scallops was modeled as a simple two-parameter logistic function of the

219 length (i.e., shell height) of scallops at age (T2.6). Since empirical size-based selectivity

220 information is lacking and there is no minimum size limit, the length at 50% vulnerability was

221 set at 35mm (pers comm, J. Granneman) -- roughly 60% of the average maximum size, and the

222 slope of the logistic function was assumed 0.5.

223 *2.4 Model Calibration/Initialization*

224 *2.4.1 Effort*

225   Harvest and effort data are largely unavailable for the Florida bay scallop fishery, and

226 thus there are no existing stock assessment models for the fishery. To initialize our population

227 model, we used effort estimates from Granneman et al. (2021), who estimated vessel effort at

228 different dates throughout the course of the 2018 scallop season in the Steinhatchee area of

229 northwest Florida (Region C, Figure 1). This data was used to estimate the total vessel effort in a

230   given month. To aggregate the daily effort counts into monthly total effort, we first fit a model to

231   the observed vessel effort as a function of the days since the first sampled effort count for that

232   month and with a random effect for the weekday of the observation (Figure S1) to account for

233   both the general decline of effort throughout the season and the weekday/weekend pattern. We

234   then predicted the effort for 90 days since the start of the scalloping season to approximate the

235   three-month season Granneman et al. (2021) observed and accounted for every possible day of

236   the week. This allowed us to calculate the total expected effort for each month in a hypothetical

237   three-month season regardless of the weekday/weekend pattern. Vessel effort was then

238   multiplied by the average persons per vessel (3.8; Granneman et al., 2021) to get the total

239   number of scallopers. The baseline catchability was also obtained from Granneman et al. (2021)

240   and divided by 3.8 to scale to average persons per vessel.

241   *2.4.2 R_0*

242   With seasonal effort and baseline catchability estimates, we then estimated the starting

243   number of recruits in the population (R_0) by minimizing the difference between model-estimated

244   average gallons (1 US liquid gallon is equivalent to 3.785 liters) of scallops caught per person at

245   equilibrium and the estimate from Granneman et al. (2021) (0.81 gallons of scallops per person).

246   To ensure our model was in equilibrium, we ran the model for 25 years and estimated (tuned) R_0

247   based on the last year's average gallons of scallops per person. For comparison purposes, we also

248   generated model results for an unfished scenario assuming $E_t = 0$.

249   *2.5 Scallop bag limit calculations*

250   The bag limit was factored into the calculation of fishing mortality by changing the

251   catchability of scallops by individual fishers. First, we calculated the catch rate of scallops in a

252 given month if there were no bag limit. We call this the catch-per-unit-effort (CPUE) and

253 calculated it by dividing the unregulated catch (not accounting for bag) by effort using:

$$(5) \ I_t = \frac{\sum_a \frac{F_{a,t}}{F_{a,t} + M_a} N_{a,t} \left(1 - e^{-(F_{a,t} + M_a)}\right) * \%Gal_a}{E_t}$$

255 Given the bag limits are specified in gallons, the numerator describing the catch at age (using the

256 Baranov catch equation; Baranov, 1918) was converted to gallons using:

$$(6) \ \%Gal = \left[\frac{(-6.704 * L_a + 480.96)}{2}\right]^{-1}$$

258 Where L_a is the length at age defined by the von Bertalanffy growth curve (T2.1). This equation

259 describes the proportion of a gallon occupied by a scallop at a given age. This formula was

260 obtained from Granneman et al. (2021) and Geiger et al. (2006). We assumed catch rates

261 followed a truncated normal distribution with a coefficient of variation of 0.455 calculated from

262 distributions of catch rates obtained in Granneman et al. (2021). We then obtained the

263 probabilities of catching any number of scallops under this distribution from 0-N, where N is set

264 at some sufficiently large number (where probability of catching N scallops approaches 0 and the

265 sum of the probabilities of catching 0-N scallops is approximately 1). The expected catch rate

266 under the bag limit ($\tilde{I}_t$) was then calculated by multiplying the probability of attaining each

267 catch rate by the number of scallops that would be retained under that catch rate (for $N > bag$,

268 number retained is equal to bag), and summing the values. We then searched for an adjusted

269 catchability value using Newton-Raphson iterations (Brent, 1973) that would produce a catch

270 rate equal to that expected under the bag limit. Note that this adjusted catchability can be thought

271 of as a realized catchability or harvestability, which represents the proportion of the population

272 harvested per unit of effort (as opposed to the catch or search efficiency for scallops). We do not

273 model any discard mortality as this is thought to be negligible in bay scallops (Benoît et al.,

274 2015).

2.6 Alternative harvest regulations assessed

276   In total, we explored ten harvest scenarios. The primary harvest regulations we evaluated

277 include the duration of the scalloping season (longer vs shorter), the timing of the season (earlier

278 vs later), and the size and nature of the bag limit (more vs less, and rolling vs fixed). A full suite

279 of management regulations that were tested is included in Table 3. In the simulation model,

280 changing the season dates changes the months which experience E_t and thus F_t. For our

281 baseline scenario, we approximated the management regulations currently in place in Citrus,

282 Hernando, and Levy Counties (Region D, Figure 1), as well as regulations similar to those used

283 in surrounding counties (Figure 1) and some novel regulations (Table 3). The size of the bag

284 limits refers to the quantity of scallops (in gallons) legally allowed per scalloper on each day, and

285 the nature of the bag limit refers to whether this amount was constant over the course of the

286 scalloping season (the same each month) or "rolling". We defined a "rolling" bag limit as one in

287 which the bag limit for the initial months of the season was lower than the limit in the final

288 months. We varied bag limits of scallops from 1, 2, and 3 gallons per scalloper per day within

289 the constant bag limit (with two gallons being the "baseline" regulation applied in most areas)

290 and explored rolling limits allowing for 1 gallon in the first month of the season to 2 gallons in

291 the final two months. We also explored the effects of lengthening the season by one month and

292 shifting the season earlier or later in the year. If an additional month was to be added to the

293 harvest season, we kept total effort for the year equivalent and reallocated it across the months

294 following the exponential decay function in subsection 2.4.1.

2.7 Uncertainty in starting conditions and effort trajectory

296   For Florida bay scallops, and likely for other annual species fisheries that are rarely

297   subjected to stock assessments, there is substantial uncertainty regarding the current exploitation

298   status as well as the trajectory of effort in the past and future. To explore the sensitivity to the

299   population starting condition, we adjusted the catchability value to generate three levels of initial

300   exploitation. Low, moderate, and high levels of initial exploitation were defined for which the

301   initial spawning escapement equaled 50%, 35%, and 20% of that in the unfished simulation after

302   the 25-year initialization period, respectively. These levels were chosen to encompass a range

303   below which different fisheries may be considered overexploited (Caddy and Mahon, 1995;

304   Clark 1991; Goodyear, 1993). Initial spawning escapement was defined as the spawning biomass

305   in the last year of the initialization period for a given simulation divided by the spawning

306   biomass produced over a year in the unfished simulation. For reference, the initial spawning

307   escapement in our model which resulted from using the catchability value from Granneman et al.

308   (2021) was 63%, and the region evaluated in Granneman et al. (2021) generally produces the

309   greatest densities of scallops (https://myfwc.com/research/saltwater/mollusc/bay-

310   scallops/season/). The new catchability values for each population starting condition were then

311   used in the process model to project the population forward under the different management

312   regulations.

313   An additional but related uncertainty in the Florida bay scallop fishery is how future

314   fishing effort will change—either in response to alternative management actions or independent

315   of them. While not well-monitored, some evidence suggests substantial increases over the last

316   decade (Granneman et al., 2021). To assess the sensitivity of harvest regulation performance to

317   future effort dynamics, we created two levels of future effort: 1) effort remained at its current

318   level for the whole simulation and 2) effort linearly increased after the initialization period such

319   that it doubled by the end of the time series relative to the starting conditions. Together, these

320   two treatment axes of initial exploitation conditions (three levels) and future effort (two levels)

321   resulted in six treatments that each harvest scenario was assessed on. Note however that these

322   scenarios do allow for effort to respond differently to the different regulations evaluated,

323   implications of which are described in the Discussion.

324   *2.8 Performance metrics*

325   Each management regulation scenario and uncertainty treatment were simulated for an

326   additional 25 years beyond the 25-year initialization period. To compare the regulation scenarios

327   across the uncertainty treatments, we compared two metrics at the end of the 50-year time series:

328   1) spawning output, and 2) harvest per unit of effort (HPUE). For the calculation of spawning

329   output, we took the mean of the total spawning biomass from the last five years of the simulation

330   (years 46-50) and divided by the spawning biomass produced over one year in the unfished

331   simulation (i.e., spawning biomass unfished). Thus, low values at the end of the simulation

332   period represent low spawning output from the population, and vice versa. For HPUE, we

333   calculated the mean harvest per unit effort of the last five years of the simulation using the

334   expected catch rate under the bag limit. We specifically used harvest per unit effort as opposed to

335   CPUE because there is no indication of socioeconomic value of catch and release in this fishery,

336   and because HPUE explicitly accounts for the imposition of bag limits, which was a key harvest

337   regulation we sought to examine.

338   *2.9 Sensitivity analysis and additional management regulations*

339   We focus mainly on results of ten main management regulations tested within the main

340   text (Table 3). However, we tested an additional 24 regulations, closer to a full factorial of all our

341   regulation treatments, and these are presented in the supplemental file. In addition, we also

342 examined the sensitivity of our results to the specification of the reference natural mortality rate

343 (M_r) and steepness (h) by increasing and decreasing them by 25% and rerunning the model and

344 management regulations (resulting in an additional 4x24 runs; Figures S2-7). We used steepness

345 instead of compensation ratio as increasing and decreasing steepness by 25% exhibits a greater

346 difference in the stock-recruit relationship than would altering CR by 25%. The base value of CR

347 = 8 converts to $h = 0.66$ ($h = CR/(CR+4)$), and the sensitivity values of $h = 0.5$ and $h = 0.83$

348 correspond to CR = 4 and CR = 20. We also present results for the metric CPUE in Figures S6-7.

349

3. Results

351   We evaluated the two performance metrics separately for all combinations of harvest

352 regulations, effort assumptions, and initial exploitation assumptions. The effects of these

353 treatments on spawning output are depicted in Figure 3, and the effects on HPUE are shown in

354 Figure 4.

3.1 Effects of harvest regulations on biological performance

356   The differences in spawning output between scenarios were larger when initial

357 exploitation was high (i.e., 20% of the initial unfished escapement rather that 50%) as well as

358 under assumptions of greater effort (row 2 [panels d, e, f], Figure 3). The effects of the scenarios

359 can be divided into three main groups. The first group contains the harvest scenario 2: increased

360 bag limit, scenario 3: decreased bag limit, scenario 4: extending the harvest season later, and

361 scenario 8: a rolling bag limit applied to the current season. This group had little effect relative to

362 the base scenario (status quo), with decreased bag limit generating more spawning output. The

363 second group includes the three scenarios involving an earlier season, scenario 5: extending the

364 harvest season earlier, scenario 7: earlier season, and scenario 10: a rolling bag with an earlier

18

365   season. This group resulted in a lower spawning output relative to the baseline. The third group

366   includes scenario 6: a later season and scenario 9: a rolling bag with a later season that resulted

367   in higher spawning output relative to the base scenario. Of these, the rolling bag with the later

368   season (scenario 9) resulted in the most spawning output. However, under the assumptions of

369   baseline effort and low initial exploitation (50% of the initial unfished escapement), no harvest

370   regulations resulted in substantial differences in spawning output, i.e., spawning output was

371   always greater than 40% of the unfished level.

372   As the levels of initial exploitation increased to moderate and high (35%, 20% of the

373   initial unfished escapement, respectively), the differences between the different harvest

374   regulations increased. The second group (scenarios 5, 7, and 10) noticeably resulted in much

375   lower spawning output at the end of the time series (<10% unfished) under the high initial

376   exploitation. In contrast, the third group (scenarios 6 and 9) still allowed for near or greater than

377   50% spawning output at the end of the time series. However, at this high initial exploitation level

378   (20% of the initial unfished escapement), the later season approach was the most robust, which

379   performed essentially as well as the decreased bag limit scenario, and was improved when

380   coupled with a rolling bag limit (Figure 3, panel c).

381   The patterns of our results described above were mirrored for the treatment of increased

382   effort, which effectively decreased the spawning output (e.g., the effective spawning output for

383   the baseline management regulations for panel d in Figure 3 is about 30%, due to the doubling of

384   effort that is only slightly muted by bag limits). The second group (three harvest regulations

385   involving earlier seasons) showed even less spawning output as expected, and the third group

386   (two scenarios involving a later season) showed little difference from the base regulations.

387   Applying the assumption of increased future effort caused three key differences in results: (i) the

388 "rolling bag, later season" (scenario 9) performed better than all other scenarios when under high

389 exploitation (20% of the initial unfished escapement); (ii) under this same assumption, decreased

390 bag limit (scenario 3) was no longer providing any real improvement relative to the baseline

391 scenario; and finally (iii) the later season (without a rolling bag) actually outperformed the other

392 rolling bags measures that did not feature a later season (scenarios 8 and 10). Thus, when the

393 doubling in effort effectively reduced the spawning output values further, the later harvest season

394 became increasingly better than other measures.

395 *3.2 Effects of harvest regulations on harvest per unit of effort*

396   Similar to spawning output at the end of the time series, HPUE was nearly equivalent

397 across different management strategies until initial exploitation increased (Figure 4). Under

398 assumptions for baseline effort and initial low or moderate exploitation (50% or 35% of the

399 initial unfished escapement; Figure 4, panels a and b), most strategies resulted in similar HPUE,

400 owing to the imposition of bag limits (as CPUE did change, Figures S6-7). However, when the

401 initial exploitation was high (20% of the initial unfished escapement; Figure 4, panel c), four

402 regulations stood out as providing greater HPUE: a decreased bag limit (scenario 3), a later

403 season (scenario 6), and the two scenarios with rolling bag limits (scenarios 8 and 9). Thus, when

404 the population is more exploited, decreasing the bag or life history-matched regulations (later

405 season or rolling bag) maintain higher harvest rates than other regulations. The pattern was

406 similar under the assumption of doubled effort (Figure 4, panels d, e, f).

407 *3.3 Sensitivity*

408   Altering the reference natural mortality rate or steepness by 25% up or down did not alter

409 which management regulations performed optimally (Figures S2-7). Of the additional 24

410 management regulations tested, scenarios 13 and 23-24 performed optimally with respect to both

411   spawning output at the end of the time series and HPUE. These refer to management regulations

412   which delay the season one month and reduce the bag limit to 1 gallon (scenario 13) or delay the

413   season one month and have rolling bag limits of 1, 1, 2 (scenario 23), and 1, 2, and 2 gallons for

414   months in the season (scenario 24) respectively. These scenarios represent a fine-tuning of the

415   best performing regulations out of the initial 10 scenarios.

416   *3.4 Summary of Results*

417   The results reveal three main findings. First, if a scallop population is known to be

418   relatively less exploited (i.e., greater spawning output, lesser effort, or both), then nearly any of

419   the harvest regulations assessed here perform similarly well. The converse of this constitutes the

420   second point: in cases where the scallop population status is either known to be more exploited,

421   or is largely unknown, harvest regulations like later seasons and rolling bag limits that are more

422   aligned with the biology and, specifically, the spawning times of this short-lived, annual species

423   will result in better biological and fishery performance (as measured by spawning output and

424   HPUE). Finally, the third finding is that there are some harvest regulations which are likely to

425   perform poorly under greater exploitation (whether from lower spawning output, greater effort,

426   or both). Specifically, any regulations that move the season earlier, and thus results in more

427   scallops being harvested prior to their spawning, risks both the lowest egg production and HPUE

428   returns.

429

430   **4. Discussion**

431   Fisheries for short-lived, annual taxa are likely to be particularly sensitive to harvest

432   timing relative to spawning. In the case of the Florida bay scallop, biologically-designed

433   regulations (e.g., later season or rolling bag) ensured some scallops spawn prior to harvest and

434   performed well across all initial exploitation levels and effort treatments in both the ecological

435   and socioeconomic metrics. Under greater initial exploitation and effort, these regulations

436   outperformed others, where they performed no worse than the others under lower initial

437   population exploitation and effort scenarios. Moreover, these regulations were much more robust

438   in our worst-case scenarios (explored as sensitivities), those being when natural mortality was

439   higher or steepness lower, coupled with higher initial exploitation and when effort increasing

440   over the time series (Figures S2-S7). This is generally consistent with the long history of

441   fisheries regulations attempting to protect some spawning individuals (Lackey, 2005), and we

442   have shown that for short-lived, annual species like the Florida bay scallop, doing so may be

443   achieved through specific timing of the harvest season.

444   The efficacy of delayed and rolling bag limits in the Florida Bay scallop fishery is

445   supported by findings of better-studied annual and/or semelparous species, as well as the few

446   studies focusing on bay scallops. While not exclusively annual species, the most well-known

447   commercially harvested semelparous species include some of the Pacific salmon and pelagic

448   squid species (Eggers, 1993; Arkhipkin et al., 2015). These populations are often managed under

449   escapement policies that require annual monitoring (Rodhouse, 2001), which is more precise but

450   conceptually similar to the harvest strategies we found performed well for the Florida bay scallop

451   fishery. Whereas escapement-based management typically relies on monitoring to determine

452   when the targeted amount of reproduction has occurred, our model identified regulations that

453   delayed much of the harvest until after spawning. Studies evaluating the harvest of bay scallop

454   populations are more sparse. One of the most comparable studies is bioeconomic investigation of

455   the North Carolina commercial bay scallop fishery (Kellogg et al., 1988). Although it did not

456   include a detailed population dynamics model and focused on commercial rather than

457   recreational objectives, it similarly concluded that delaying harvest seasons would optimize

458   profits. Additionally, Granneman et al. (2021) estimated bay scallop pre- and post-season

459   population size, harvest, and effort for 2018 in the Steinhatchee area of the Florida Gulf Coast,

460   although they also did not include a population dynamics model with stock and recruitment.

461   They evaluated various management strategies with respect to season lengths and effort levels

462   and found similar results to this study where under the current management regulations, a

463   doubling of effort would likely extirpate the population. In addition, they estimated that rolling

464   bag limits would also lead to increased post-season bay scallop populations.

465   The main management implication of this work is that biologically designed harvest

466   regulations provide better outcomes, especially under uncertainty (e.g., actual population size

467   and effort levels). The results emphasize that there are essentially two management strategies for

468   sustaining the egg production of scallops. The first is to maintain a fishery at relatively low

469   levels of exploitation. Though requiring substantial, more costly annual monitoring to assess, this

470   would allow for the imposition of a broad range of harvest regulations. The second approach

471   would be to employ biologically designed harvest regulations that specifically delay some

472   harvest until more scallops have likely spawned. The outcomes in the biological and

473   socioeconomic metrics show that a biologically-designed approach performs well under nearly

474   all exploitation scenarios. This implies that biologically-designed harvest approaches will likely

475   be effective even in absence of a substantial monitoring program by ensuring a sufficient

476   proportion survive to spawn. If the actual exploitation is low but also unknown, these harvest

477   regulations will at worst perform barely below other approaches, whereas if the exploitation is

478   higher, they will perform substantially better. However, this harvest approach notably does not

479   reduce effort capacity, leaving the fishery vulnerable to increases in total effort (Mullon et al.,

480 2005). Thus, the primary finding of our work aligns with Young et al. (2006); there is little

481 reason to not apply biologically designed regulations to short-lived and annual fisheries.

482 However, what these biologically designed regulations should be may differ across species and

483 fisheries. For many annual species, it is likely a delayed harvest season and rolling bag limit will

484 work well, but the specific harvest strategy and timing should be investigated on a case-by-case

485 basis.

486   The approach we used provides a blueprint for evaluating management regulations for

487 other short-lived, annual recreational fisheries where catch and effort data are sparse.

488 Recreational fisheries for these types of species are common and popular (e.g., Lellis-Dibble et

489 al., 2008; Taylor 2017; Aguilera, 2018; Ben-Hasan, 2018; Sydeman et al., 2020), but harvest

490 regulations are not often evaluated (Forbes et al., 2019). Quantitative evaluation of these

491 fisheries can be complicated by at least two factors, and we demonstrate how both may be

492 addressed. The first challenge is that annual species life histories are not generally well-

493 represented by modern fisheries population dynamics modeling (Martell et al., 2008), in which

494 spawning is generally iteroparous and occurs once per modeled time step. Complete or partial

495 semelparity and corresponding periodic recruitment can be achieved by using monthly time steps

496 (as opposed to annual) with simple timing skips (spawning ever nth time step) and incorporating

497 this into recruitment calculations (T2.3 and T2.9). The second complication is that recreational

498 fisheries for these types of short-lived species will often involve bag limits (Hartill et al., 2005;

499 Reid and Montgomery, 2005; Obregón, 2020). Bag limits are easy to implement in individual-

500 based models (IBMs) but challenging in the population and fishery-level models that are most

501 commonly employed (Martell et al., 2008). Our approach provides a more mechanistic

502 description of how changing bag limits will translate to altered total harvest, which builds off

503 what has been used in earlier recreational fisheries evaluations (Forbes et al., 2019).

504 Application of our approach should consider several assumptions that could not be

505 verified, and which could affect outcomes. An important one is the implicit assumption that the

506 HPUE metric is sufficient to represent socioeconomic objectives of the fishery. This assumption

507 would be inappropriate for many, if not most, longer-lived finfish recreational fisheries, where

508 the size and rate of catch and harvest are critical components of utility (Hunt et al., 2019), but is

509 probably more appropriate for Florida bay scallops that are gathered (not angled) at a more

510 uniform size compared to most finfish (Granneman et al., 2021). Furthermore, the

511 recommendations we made are conservative with respect to any (unknown) preference for size in

512 that the average size of harvested scallops is likely to increase under the biologically-designed

513 regulations we have recommended. If this modeling approach is applied to other fisheries with

514 perhaps more diverse motivations or types of fishers, multi-attribute utility per trip metrics

515 (Camp et al., 2019; van Poorten and Camp, 2019) or some measure of satisfaction (Birdsong et

516 al., 2021) should be considered. Those approaches should also be applied to future bay scallop

517 work if emerging evidence suggests non-harvest utility or satisfaction is affected by harvest

518 regulations (e.g., regulations increasing congestion or leading to harvest seasons overlapping

519 with less enjoyable weather).

520 Two other important considerations not assessed in this study include scallops

521 metapopulation structure and the political economy of local scallop management. This work

522 considered a single population that supplies its own spawning biomass and thus recruits because

523 this simple approach increases the clarity of the results and matches the current regional scallop

524 management approach. However, there is some evidence that more complex metapopulation

525 dynamics exist, with local populations being subsidized by larvae from other populations

526 (Arnold et al., 1998; Bert et al., 2014). If in the future such metapopulation structure can be

527 understood well enough to assess the probabilities of larvae spawned in one region settling in

528 another, spatial population modeling should be used to assess population sources and sinks.

529   Regardless of metapopulation structure, future studies should assess how harvest

530 regulations implemented differently across the region could directly or indirectly affect effort

531 and the potential landscape consequences of this. By testing scenarios in which overall effort

532 increased in the future, we account for long-term changes in effort independent of regulations,

533 but not for effort dynamics driven directly by regulations or indirectly by regulatory-induced

534 population changes. Empirical (Johnson and Carpenter, 1994; Beard et al., 2003; Post and

535 Parkinson, 2012) and theoretical (Hunt et al., 2011; Allen et al., 2013) studies suggest that

536 altered harvest restrictions can affect fishing effort in some fisheries, though the direction of the

537 effect is not always intuitive (Hurley and Jackson, 2002). Thus, it is possible that the alternative

538 regulations we explore could differently affect scallop fishing effort, which could instigate

539 effort-population feedbacks and alter our results. Future work studying this should assess, such

540 as by stated preference choice experiment, the part-worth utility functions influencing scalloper

541 decision-making. Borrowing those estimated for fin-fisheries (reviewed in Hunt et al., 2019) may

542 be inappropriate because of differences between often challenge-motivated fin-fisheries and

543 scallop fisheries that are more gathering. Such models could consider not only consumer demand

544 for scallops but also the political economy governing regional management decisions. Here, we

545 have implicitly assumed a shift in the harvest season is sufficiently palatable to decision-makers.

546 In reality, shifting towards a later harvest season, including one that occurs after the current

547 summer season closes, may reduce the demand for scallop fishing and alter the economic

548 contribution of the fishery. Recreational scalloping is a family-oriented activity, with peak

549 participation in the summertime holidays and on the weekends (Granneman et al., 2021). As the

550 season progresses, there are fewer scallop trips, which may be attributable to the start of the

551 school year, hunting season, and hurricane season. Evaluating the socioeconomic effects of a

552 later-shifted season would require assessing the economic contribution to local economies and

553 how fishers are likely to behave under the new regulations. The absence of information about

554 scalloper behavior precluded a dynamic effort component of this model but revealed or stated

555 preference choice studies could address both these issues. Estimating a mechanistic and

556 predictive model of scallop effort would facilitate developing landscape models for testing how

557 population and regulatory changes in one region could affect others, per van Poorten and Camp

558 (2019). This is critical to avoid triggering cascading or unintended consequences for the regional

559 scallop population and fishery.

560

561 **5. Conclusions**

562   This work demonstrates that biologically-designed harvest regulations that consider the

563 overlap between harvest and spawning seasons are likely to provide ecological and

564 socioeconomic advantages over approaches currently employed for the bay scallop fishery in

565 Florida. Regulations such as later harvest seasons and rolling bag limits likely buffer against

566 uncertainty in the depletion level of the population. While many short-lived, annual species

567 exhibit harvest seasons presumably designed with respect to their spawning, this is one of the

568 first studies to quantitatively evaluate it. It provides a modeling framework that may be more

569 broadly applicable to other taxa. This template might be expanded via future research to allow

570   for more mechanistic descriptions of fisher utility, decision making, and implications for local

571   economic contribution.

572

573   **CRediT authorship contribution statement**

574   **Lisa Chong:** Methodology, Formal analysis, Writing – Investigation, Visualization, Review &

575   editing. **Nicholas Fisch:** Methodology, Formal analysis, Writing – Original draft, Investigation,

576   Review & editing. **John Scott Borsum:** Writing – Original draft, Review & editing. **Jennifer**

577   **Granneman:** Writing - Review & editing. **Diana Perry:** Writing - Original draft, Review &

578   editing. **Gabrielle Love:** Writing - Review & editing. **Brittany Hall-Scharf:** Writing - Review

579   & editing. **Robert Botta:** Writing - Review & editing. **Kai Lorenzen:** Writing - Review &

580   editing. **Edward Camp:** Supervision, Conceptualization, Methodology, Writing – Original draft,

581   Investigation, Review & editing. **Zachary Siders:** Supervision, Methodology, Writing –

582   Investigation, Visualization, Review & editing.

583

584   **Declaration of Competing Interest**

585   The authors report no declarations of interest.

586

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590   this manuscript.

591

6. Supplementary information

Table S1. Management regulations tested. When bag limit is presented in parentheses, it refers to the bag limit for each open month of the fishing season.

Figure S1. Results of generalized linear mixed model fit to the logarithm-transformed effort as a function of day with a random effect for weekday. The observed data from Granneman et al. (2021) is shown in black circles and the model-based predictions are shown in the red line.

Figure S2. Results of spawning output relative to unfished for the different management regulations simulated in this study under different starting levels of population exploitation (columns, only low and high depicted here) and different assumptions about the level of effort expended between years (rows). The first row depicts a scenario with constant effort in each year of the simulation, where the second row depicts a scenario with effort doubling over the course of the 25-year simulation period. The horizontal lines depict the sensitivity analysis for natural mortality ($M = 0.25$), where the red lines represent 25% decrease in natural mortality ($M = 0.19$) and the orange lines represent 25% increase in natural mortality ($M = 0.32$).

Figure S3. Results of spawning output relative to unfished for the different management regulations simulated in this study under different starting levels of population exploitation (columns, only low and high depicted here) and different assumptions about the level of effort expended between years (rows). The first row depicts a scenario with constant effort in each year of the simulation, where the second row depicts a scenario with effort doubling over the course of the 25-year simulation period. The horizontal lines depict the sensitivity analysis for steepness ($h = 0.67$; $CR = 8$), where the red lines represent 25% decrease in steepness (50% decrease in

613   compensation ratio; h = 0.5 and CR = 4) and the orange lines represent 25% increase in

614   steepness (150% increase in compensation ratio; h = 0.83 and CR = 20).

615   **Figure S4**. Results of harvest per unit of effort for the different management regulations

616   simulated in this study under different starting levels of population exploitation (columns, only

617   low and high depicted here) and different assumptions about the level of effort expended

618   between years (rows). The first row depicts a scenario with constant effort in each year of the

619   simulation, where the second row depicts a scenario with effort doubling over the course of the

620   25-year simulation period. The horizontal lines depict the sensitivity analysis for natural

621   mortality (M = 0.25), where the red lines represent 25% decrease in natural mortality (M = 0.19)

622   and the orange lines represent 25% increase in natural mortality (M = 0.32).

623   **Figure S5**. Results of harvest per unit of effort for the different management regulations

624   simulated in this study under different starting levels of population exploitation (columns, only

625   low and high depicted here) and different assumptions about the level of effort expended

626   between years (rows). The first row depicts a scenario with constant effort in each year of the

627   simulation, where the second row depicts a scenario with effort doubling over the course of the

628   25-year simulation period. The horizontal lines depict the sensitivity analysis for steepness (h =

629   0.67; CR = 8), where the red lines represent 25% decrease in steepness (50% decrease in

630   compensation ratio; h = 0.5 and CR = 4) and the orange lines represent 25% increase in

631   steepness (150% increase in compensation ratio; h = 0.83 and CR = 20).

632   **Figure S6.** Results of catch per unit of effort for the different management regulations simulated

633   in this study under different starting levels of population exploitation (columns, only low and

634   high depicted here) and different assumptions about the level of effort expended between years

635   (rows). Catch per unit effort includes both scallops harvested and scallops caught and released in

636   order to comply with the bag limit. The first row depicts a scenario with constant effort in each

637   year of the simulation, where the second row depicts a scenario with effort doubling over the

638   course of the 25-year simulation period. The horizontal lines depict the sensitivity analysis for

639   natural mortality ($M = 0.25$), where the red lines represent 25% decrease in natural mortality (M

640    $= 0.19$) and the orange lines represent 25% increase in natural mortality ($M = 0.32$).

641   **Figure S7**. Results of catch per unit of effort for the different management regulations simulated

642   in this study under different starting levels of population exploitation (columns, only low and

643   high depicted here) and different assumptions about the level of effort expended between years

644   (rows). Catch per unit effort includes both scallops harvested and scallops caught and released in

645   order to comply with the bag limit. The first row depicts a scenario with constant effort in each

646   year of the simulation, where the second row depicts a scenario with effort doubling over the

647   course of the 25-year simulation period. The horizontal lines depict the sensitivity analysis for

648   steepness ($h = 0.67$; $CR = 8$), where the red lines represent 25% decrease in steepness (50%

649   decrease in compensation ratio; $h = 0.5$ and $CR = 4$) and the orange lines represent 25% increase

650   in steepness (150% increase in compensation ratio; $h = 0.83$ and $CR = 20$).

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Figure captions

Figure 1. Map of Big Bend region of Florida (red rectangle in inset) depicting the five scalloping zones (A-E). Zone D (depicted in orange) was the area chosen for the baseline management regulations in this study and spans Levy, Citrus, and Hernando counties. The per person bag limit in gallons of whole scallops as well as the dates for the open and close of the scalloping season are provided in the table by zone. Note that zone C has a rolling bag limit that is 50% lower in the first 15 day of the season.
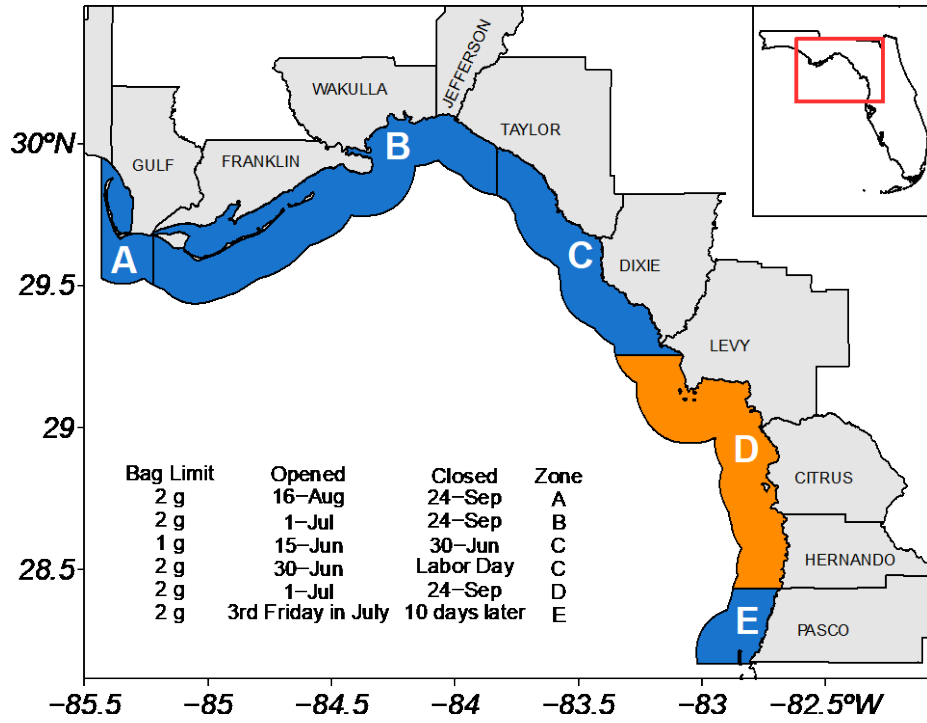
Figure 2. The shell height at age (A), weight at age (B), selectivity at age (C), proportion mature at age (D), and natural mortality at age (E) for bay scallops calculated from the life history parameters assumed in the simulation model.

Figure 3. Results of spawning output relative to unfished for the different management regulations simulated in this study under different starting levels of population exploitation (columns) and different assumptions about the level of effort expended between years (rows). The first row depicts a scenario with constant effort in each year of the simulation, where the second row depicts a scenario with effort doubling over the course of the 25-year simulation period.

Figure 4. Results of harvest per unit of effort for the different management regulations simulated in this study under different starting levels of population exploitation (columns) and different assumptions about the level of effort expended between years (rows). The first row depicts a
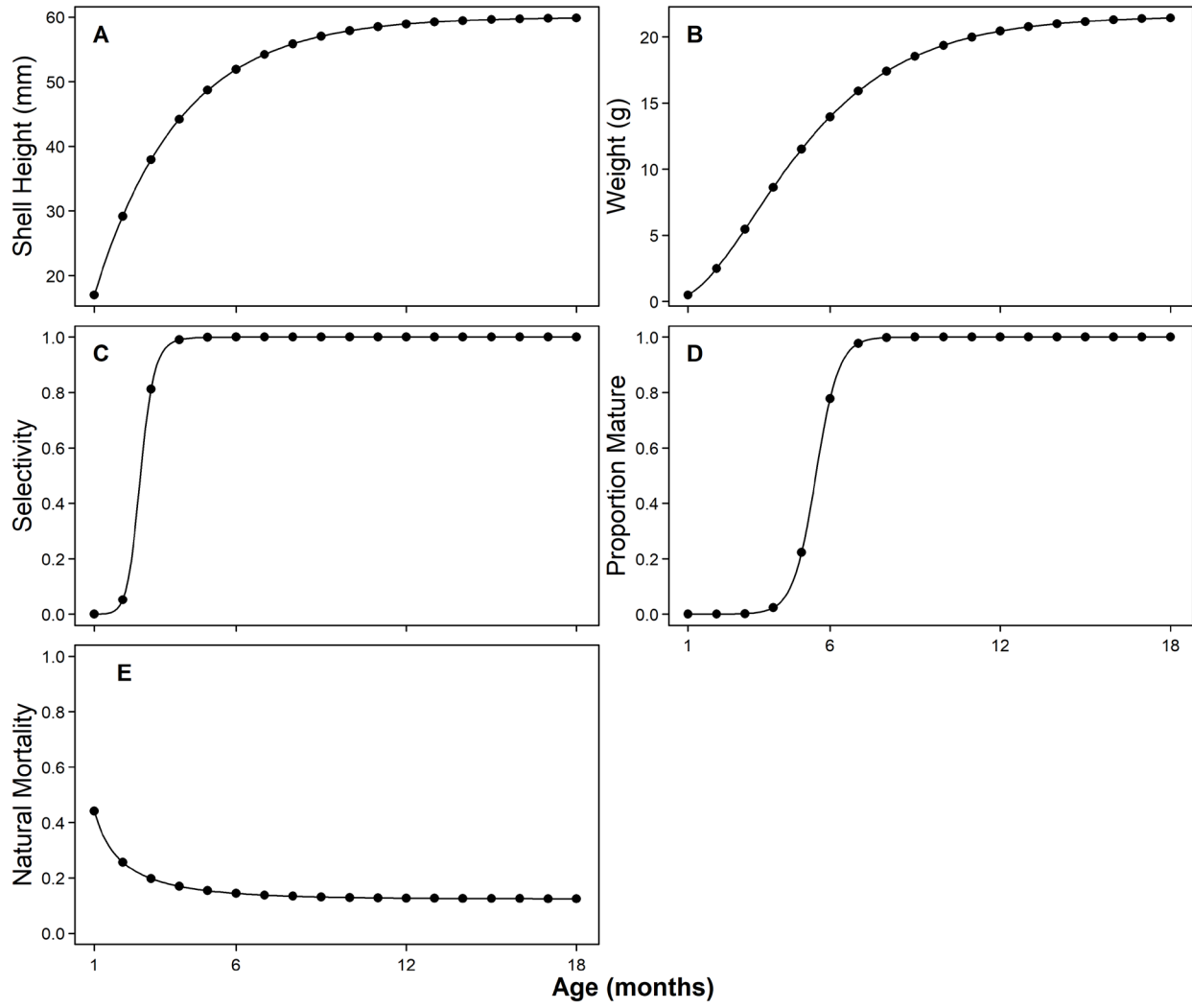
838   scenario with constant effort in each year of the simulation, where the second row depicts a

839   scenario with effort doubling over the course of the 25-year simulation period.

1 Figures

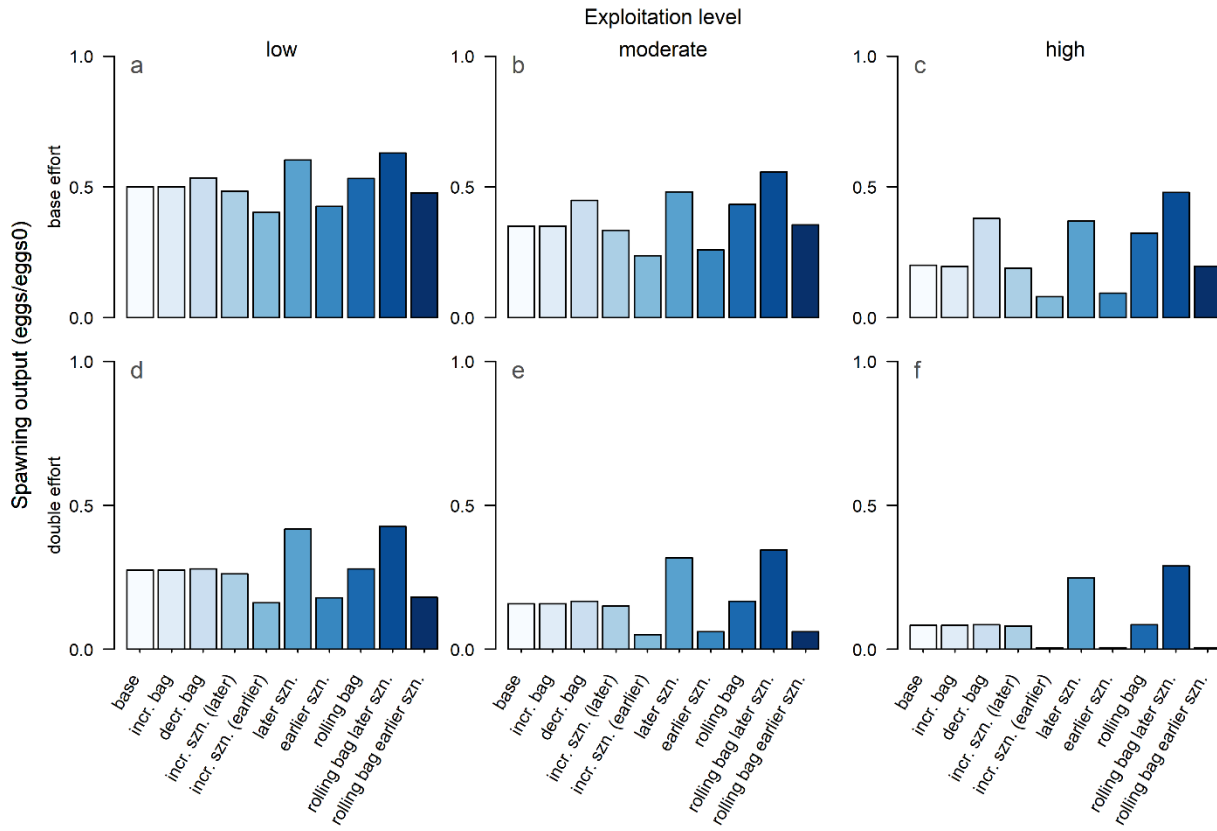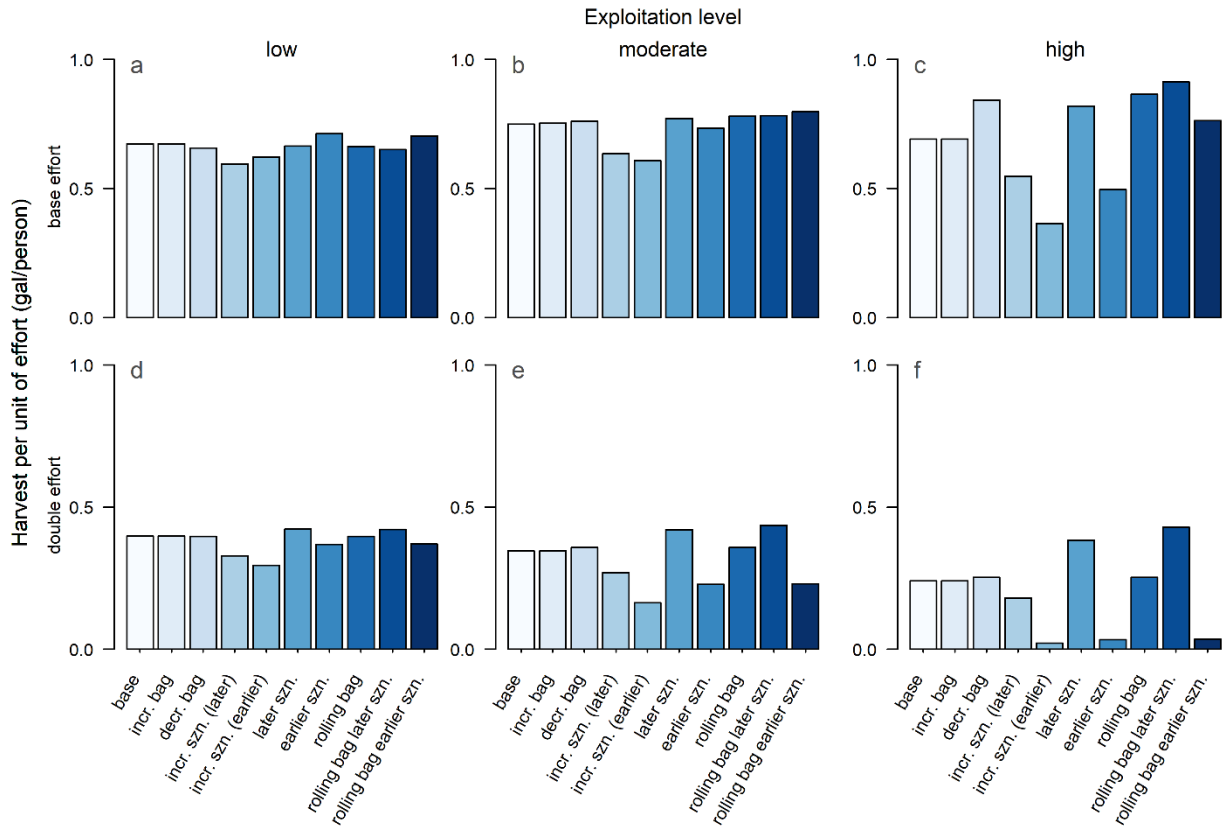| Bag Limit	Opened	Closed	Zone
2 g	16–Aug	24–Sep	A
2 g	1–Jul	24–Sep	B
1 g	15–Jun	30–Jun	C
2 g	30–Jun	Labor Day	C
2 g	1–Jul	24–Sep	D
2 g	3rd Friday in July	10 days later	E

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3 **Figure 1.**

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5   **Figure 2.**

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8   **Figure 3.**

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11 **Figure 4.**

Tables

Table 1. Parameters used in the bay scallop simulation model and their source. We provide more detail on how the source material led to the parameter values in the supplemental.

Description	Parameter	Value	Source
Life History			
Asymptotic length	L_∞	60	Barber and Blake (1983); Leverone et al. (1992); Geiger et al. (2006)
Brody growth coefficient	K	1/3	Barber and Blake (1983); Leverone et al. (1992); Geiger et al. (2006)
Theoretical age at size 0	t_0	0	Arbitrary
Length-weight a parameter	a	0.0001	Arbitrary
Length-weight b parameter	b	3	Standard cubic
Natural mortality at reference length	M_r	0.25	Granneman et al. (2021)
Allometric exponent	c	-1	Arbitrary (default)
Reference length	L_r	$L_\infty / 2$	Arbitrary (default)
Unfished recruitment	R_0	Calibrated	Calibrated to achieve estimated average gallons of scallops per person similar to that found in Granneman et al. (2021)
Compensation ratio	CR	8	Arbitrary
Maturity parameter 1 (Age at 50% maturity)	ν	5.5	Blake (1972); Barber and Blake (1983); Shumway and Parsons (2016)
Maturity parameter 2 (Growth rate of logistic function)	ς	2.5	Blake (1972); Barber and Blake (1983); Shumway and Parsons (2016)
Fecundity-weight scalar	η	0.1	Arbitrary

Gonadal-somatic index	GS_{month}	[0.05,0.05,0.05,0.05, 0.05,0.05,0.05,0.09, 0.125,0.09,0.07,0.05]	Fig 5. Geiger et al. (2006)
Probability of spawning in a given month	$\psi_{month} = GS_{month} / \sum\limits_{month=Jan}^{Dec} GS_{month}$		GS_{month}
Management			
Selectivity Parameter 1 (length at 50% vulnerable)	κ	35	Arbitrary
Selectivity Parameter 2 (growth rate of logistic function)	τ	0.5	Arbitrary
Catchability*	q	0.0000319/3.8	Granneman et al. (2021)
Monthly Effort throughout the course of a year	E_{month}	[0,0,0,0,0,0,11415,6 929,4255,0,0,0]*3.8	Granneman et al. (2021)
Effort between years	$E_t = f(E_{month})$	Constant or linearly increasing to double the initial annual effort at the end of time series	Arbitrary, used as simulation treatment (see section 2.8 on uncertainty of starting conditions)

*Note that this is the catchability value which was used to estimate R_0, three different values were used to project the population according to the population starting condition scenarios.

Table 2. Various equations used in the bay scallop simulation model.

Equation	Description	Equation
T2.1	Shell height at age	$L_a = L_\infty \left(1 - e^{\left(-K(a-t_0)\right)}\right)$
T2.2	Weight at age	$W_a = aL_a^b$
T2.3	Natural mortality	$M_a = \begin{cases} M_r \left(L_a \big/ L_r\right)^c & \text{for } 0 \le a \le 18 \\ \infty & \text{for } a > 18 \end{cases}$
T2.4	Maturity	$Mat_a = 1 \big/ 1 + e^{-\varsigma(a-v)}$
T2.5	Fecundity	$Fec_a = \eta W_a$
T2.6	Fishery Selectivity	$s_a = 1 \big/ 1 + e^{-\tau(L_a - \kappa)}$
T2.7	Alpha Beverton-Holt	$\alpha = \dfrac{CR}{\Phi_0}$
T2.8	Beta Beverton-Holt	$\beta = \dfrac{CR - 1}{R_0 * \Phi_0}$
T2.9	Unfished eggs per recruit	$\Phi_0 = \sum_a l_a * Mat_a * \psi_a * \omega_a * Fec_a$
T2.10	Survivorship at age in unfished condition	$l_a = \begin{cases} 1 & \text{if } a = 1 \\ l_{a-1}e^{-(M_{a-1})} & \text{if } a > 1 \end{cases}$
T2.11	Baranov Catch Equation	$C_{a,t} = \dfrac{F_{a,t}}{F_{a,t} + M_a} N_{a,t} \left(1 - e^{-\left(F_{a,t} + M_a\right)}\right)$

Table 3. Management regulations tested in this study. When bag limit is presented in parentheses it refers to the bag limit for each open month of the fishing season. We defined a "rolling" bag limit as one in which the bag limit for the initial months of the season was lower than the limit in the final months. A "fixed" bag limit refers to a single bag limit that is set throughout the season per month.

Number	Name	Bag Limit (gallons)	Bag Type	Season Length (months)	Season Start	Season End
1	Base	2	Fixed	3	July	Sept
2	Increased bag	3	Fixed	3	July	Sept
3	Decreased bag	1	Fixed	3	July	Sept
4	Increased season (later)	2	Fixed	4	July	Oct
5	Increased season (earlier)	2	Fixed	4	June	Sept
6	Later season	2	Fixed	3	Aug	Oct
7	Earlier season	2	Fixed	3	June	Aug
8	Rolling bag limit	(1,2,2)	Rolling	3	July	Sept
9	Rolling bag limit and later season	(1,2,2)	Rolling	3	Aug	Oct
10	Rolling bag limit and earlier season	(1,2,2)	Rolling	3	June	Aug