

# Highly resolved spatiotemporal simulations for exploring mixed fishery dynamics

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## Abstract

To understand how data resolution impacts inference on mixed fisheries interactions we developed a highly resolved spatiotemporal discrete-event simulation model ('MixFishSim') incorporating: i) delay-difference population dynamics, ii) population movement using Gaussian Random Fields to simulate patchy, heterogeneously distributed and moving fish populations, and iii) fishery dynamics for multiple fleet characteristics based on population targeting under an explore-exploit strategy. ~~This is implemented via a mix of correlated random walk movement (for exploration) and learned behaviour (for exploitation) phases of the fisheries.~~

~~Fifty years of sub-daily fishing activity was simulated and used to draw inference on the underlying community structures. We applied the framework to draw compared inferences on community structure when using data generated from based on: commercial catch, a simulated fixed-site sampling survey design and the true (simulated) underlying populations. In doing so we i) establish the potential limitations of fishery-dependent data in providing a robust picture of spatiotemporal distributions; and then ii) simulated an area closure based on areas defined from the different data sources at a range of temporal and spatial resolutions. Our~~

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~~framework allows users to explore the assumptions in modelling observational data and evaluate the underlying dynamics of such approaches at a fine spatial and temporal scale. In application to a mixed fishery exploiting four different populations w~~ We found different spatial patterns were evident and that the effectiveness of the spatial closure reduced when data were aggregated across larger spatial areas. ~~;~~ ~~and then ii)~~ We then simulated an area closure based on areas defined from the different data sources at a range of temporal and spatial resolutions. Aggregation across time periods has less of a negative impact on the closure success than over space. ~~and w~~ While not as effective as when based on on the true population, closures based on high catch rates observed in commercial data were still able to reduce fishing on a protected species.

Our framework allows users to explore the assumptions in modelling observational data and evaluate the underlying dynamics of such approaches at a fine spatial and temporal scale. From our application wWe conclude that commercial data, while containing bias, provide a useful tool for managing catches in mixed fisheries if applied at the correct spatiotemporal scale.

*Keywords:* spatiotemporal, mixed fisheries, individual based, spatial management, heterogeneity, bycatch avoidance

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## 1. Introduction

Fishers exploit a variety of fish populations that are heterogeneously distributed in space and time with varying knowledge of species distributions. As fishers do not have full control over what species they select when fishing in ‘mixed fisheries’ it can result in catch of low quota or protected species. If over-quota catch of a species for which they have no quota is discarded without being accounted for it limits our ability to control fishing mortality (Alverson et al., 1994; Crowder et al., 1998; Rijnsdorp et al., 2007) and the ability to manage

9 fisheries for the biological and economic sustainability (Ulrich et al., 2011; Bat-  
10 sleer et al., 2015).

11  
12 There is increasing interest in technical solutions such as gear and spatial clo-  
13 sures as measures to reduce unwanted catch (Kennelly and Broadhurst, 2002;  
14 Catchpole and Reville, 2008; Bellido et al., 2011; Cosgrove et al., 2019) and  
15 adaptive spatial management strategies have been proposed as a way of reduc-  
16 ing over-quota discards (Holmes et al., 2011; Little et al., 2015; Dunn et al.,  
17 2014). However, if fisheries are to reduce unwanted catch through spatial avoid-  
18 ance, an in-depth understanding of spatiotemporal fishery dynamics is required.

19  
20 Understanding the correct scale for spatial management measures to be effec-  
21 tive is crucial as it enables implementation of effective solutions which minimise  
22 economic impact (Dunn et al., 2016). For example, the problem can be to iden-  
23 tify a scale that promotes species avoidance for vulnerable or low quota species  
24 while allowing continuance of sustainable fisheries for available quota species.  
25 Identifying the correct spatial scale remains a challenge because data on fish  
26 location at high temporal and spatial resolutions is expensive and difficult to  
27 collect and proxies are usually inferred from scientific surveys or commercial  
28 catches with limited spatial and temporal resolution. Thus, implementation of  
29 spatial measures is hampered by a lack of knowledge of fish and fishery spa-  
30 tiotemporal dynamics and understanding of the scale at which these processes  
31 become important for management.

32  
33  
34 Identifying appropriate spatial scales for fisheries closures has been a high-  
35 lighted as crucial to their success (Costello et al., 2010; Dunn et al., 2016).  
36 Inference on fisheries spatial dynamics is hampered where spatial information  
37 is coarse due to low resolution reporting of fisheries catch which is aggregated  
38 across larger gridded areas (Branch et al., 2005). Further, if data does not allow  
39 identification of spatial features it may lead to poorly sited closures which are

ineffectual or have unintended consequences. For example, increased benthic impact on previously unexploited areas from the cod closure in the North Sea were observed without the intended effect of reducing cod exploitation (Rijnsdorp et al., 2001; Dinmore et al., 2003)).

More refined spatiotemporal information has since become available through the combination of logbook and Vessel Monitoring System (VMS) data (Lee et al., 2010; Bastardie et al., 2010; Gerritsen et al., 2012; Mateo et al., 2017) and more real-time spatial management has been possible (e.g. Holmes et al., 2011). However, fishers establish favoured fishing grounds through an explore-exploit strategy (Rijnsdorp et al., 2011; Bailey et al., 2019) where they search for areas with high catches and then use experience to return to areas where they’ve experienced high catch in the past. This leads to an inherently biased sampling where target species are over-represented in the catch as fishers exploit areas of high abundance. There is a need to understand the influence of these biases on any spatial management measures which are implemented based on inference from commercial landings or catch data.

To understand the effect of spatiotemporal aggregation of data and fishery targeting on our perception of spatial abundance of different fish populations we ask two fundamental questions regarding inference derived from observational data:

1. Do different source of sampling-derived fisheries data reflect the underlying community structure?
2. How does data aggregation and data source impact on the success of spatial fisheries management measures?

To answer these questions we i) develop a simulation model where population dynamics are highly-resolved in space and time, using a Gaussian spatial process to define suitable habitat for different populations. As the precise locations of the fish are known directly rather than inferred from sampling or

commercial catch, we can use the population model to validate how inference from fisheries-dependent and fisheries independent sampling relates to the real community structure in a way we could not with real data. We ii) compare, at different spatial and temporal aggregations, the real (simulated) population distributions to samples from fisheries-dependent and fisheries independent catches to test if these are a true reflection of the relative density of the populations. We then iii) simulate a fishery closure to protect a species based on different spatial and temporal data aggregations.

We use these evaluations to draw inference on the utility of commercial data in supporting management decisions.

## 2. Materials and Methods

A Discrete-event simulation (DES) model of a hypothetical fishery was developed as a software package (*MixFishSim*). The modular approach enabled efficient computation by allowing for sub-modules implemented on time-scales appropriate to capture the characteristic of the different processes (Figure 1). The following sub-modules were included to capture the full system: 1) Population dynamics, 2) Recruitment dynamics, 3) Population movement, 4) fishery dynamics.

Population dynamics for any number of species, as chosen by the user operate on a daily time-step (with recruitment occurring only during defined seasons for each population), while population movement occurs on a weekly time-step, with the fishing module operating on a tow-by-tow basis (i.e. multiple events a day).

### 2.1. Population dynamics

The basic population level processes were simulated using a modified two-stage Deriso-Schnute delay difference model which models the fish populations in

terms of aggregate biomass of recruits and mature components rather than keeping track of individuals (Deriso, 1980; Schnute, 1985; Dichmont et al., 2003). A daily time-step was chosen to discretise continuous population processes on a biologically relevant and computationally tractable timescale. Population biomass growth was modelled as a function of previous recruited biomass, intrinsic population growth and recruitment functionally linked to the adult population size. Biomass for each cell  $c$  was incremented each day  $d$  as follows (the full parameter list is detailed in Table 1):

$$\begin{aligned}
B_{c,d+1} = & \\
& (1 + \rho) B_{c,d} \cdot e^{-Z_{c,d}} - \rho \cdot e^{-Z_{c,d}} \quad \times \\
& (B_{c,d-1} \cdot e^{-Z_{c,d-1}} + Wt_{R-1} \cdot (\alpha_{d-1} \cdot R_{\tilde{y}(c)})) \quad + \\
& Wt_R \cdot (\alpha_d \cdot R_{\tilde{y}(c)})
\end{aligned} \tag{1}$$

where  $\rho$  is Brody's coefficient, shown to be equal to  $e^{-K}$  when  $K$  is the growth rate from a von Bertalanffy logistic growth model (Schnute, 1985).  $Wt_{R-1}$  is the average weight of fish prior to recruitment, while  $Wt_R$  is the average recruited weight.  $\alpha_d$  represents the proportion of fish recruited during that day for the year, while  $R_{c,\tilde{y}(c)}$  is the annual recruits in year  $y$  for cell  $c$ .

Mortality  $Z_{c,d}$  can be decomposed to natural mortality,  $M_{c,d}$ , and fishing mortality,  $F_{c,d}$ , where both  $M_{c,d}$  and  $F_{c,d}$  are instantaneous rates with  $M_{c,d}$  fixed and  $F_{c,d}$  calculated by solving the Baranov catch equation (Hilborn and Walters, 1992) for  $F_{c,d}$ :

$$C_{c,d} = \frac{F_{c,d}}{F_{c,d} + M_{c,d}} \cdot \left(1 - e^{-(F_{c,d} + M_{c,d})}\right) \cdot B_{c,d} \tag{2}$$

where  $C_{c,d}$  is the summed catch from the fishing model across all fleets and vessels in cell  $c$  for the population during the day  $d$ , and  $B_{c,d}$  the daily biomass for the population in the cell. Here, catch is the sum of those across all fleets and vessels,  $C_{c,d} = \sum_{fl=1}^{FL} \sum_{v=1}^V E_{fl,v,c,d} \cdot Q_{fl} \cdot D_{c,d}$  with  $fl$  and  $FL$  the fleet and total number of fleets,  $v$  and  $V$  the vessel and total number of vessels respectively and  $E_{fl,v,c,d}$  and  $Q_{fl}$  fishing effort and catchability of the gear, and  $D_{c,d}$  is the

123 density of the population at the location fished.

124

## 125 2.2. Recruitment dynamics

126 Recruitment is modelled as a function of adult biomass. In *MixFishSim*, it  
127 can either take the form of a stochastic Beverton-Holt stock recruitment relation-  
128 ship, or a stochastic Ricker stock recruitment relationship. The Beverton-Holt  
129 relationship is defined as (Beverton and Holt, 1957):

$$\begin{aligned}\bar{R}_{c,d} &= \frac{(\alpha \cdot S_{c,d})}{(\beta + S_{c,d})} \\ R_{c,d} &\sim \log N[(\log(\bar{R}_{c,d}), \sigma^2)]\end{aligned}\tag{3}$$

130 where  $\alpha$  is the maximum recruitment rate,  $\beta$  the spawning stock biomass (SSB)  
131 required to produce half the maximum stock size,  $S$  current stock size and  $\sigma^2$   
132 the variability in the recruitment due to stochastic processes. The stochastic  
133 Ricker form (Ricker, 1954) is:

$$\begin{aligned}\bar{R}_{c,d} &= B_{c,d} \cdot e^{(\alpha - \beta \cdot B_{c,d})} \\ R_{c,d} &\sim \log N[(\log(\bar{R}_{c,d}), \log(\sigma^2))]\end{aligned}\tag{4}$$

134 where  $\alpha$  is the maximum productivity per spawner and  $\beta$  the density dependent  
135 reduction in productivity as the SSB increases.

## 136 2.3. Population movement dynamics

137 Population movement is a combination of directed (advective) movement  
138 where at certain times of year the population moves towards spawning grounds  
139 by increasing the probabilities of moving into the spawning grounds from adja-  
140 cent cells, and random (diffusive) movement, governed by a stochastic process  
141 where movement between adjacent cells is described by a set of probabilities  
142 which are affected by the suitability of habitat, temperature in a cell and the  
143 thermal tolerance of a population to that temperature.

144

145 The combined process results in a population structure and movement pat-  
146 tern unique to each population, with population movement occurring on a

147 weekly basis. The decision to model population movement on a weekly timescale  
 148 was to reflect that fish tend to aggregate in species specific locations that have  
 149 been observed to last around one to two weeks (Poos and Rijnsdorp, 2007b).  
 150 Therefore this process approximated the demographic shifts in fish populations  
 151 throughout a year with seasonal spawning patterns (Figure S3).

152 To simulate fish population distribution in space and time a Gaussian spa-  
 153 tial process was employed to model habitat suitability for each of the popula-  
 154 tions on a 2d grid. We first defined a Gaussian random field process,  $\{S(c) : c \in \mathbb{R}^2\}$ ,  
 155 where for any set of cells  $c_1, \dots, c_n$ , the joint distribution of  $S = \{S(c_1), \dots, S(c_n)\}$   
 156 is multivariate Gaussian with a *Matérn* covariance structure, where the correlation strength  
 157 weakens with distance controlled by two parameters, with  $\nu$  a scale parameter in the units of  
 158 distance and  $\kappa$  a shape parameter which determines the smoothness of the process. We use the  
 159 most commonly used Matérn covariance structure as it is a flexible form that under certain  
 160 conditions is of the same form as an exponential function and itThis enables  
 161 us to model the spatial autocorrelation observed in animal populations where  
 162 density is more similar in nearby locations, but that correlation decreases non-  
 163 linearly (Tobler, 1970; F. Dormann et al., 2007; Poos and Rijnsdorp, 2007b).  
 164 We change the parameters to implement different spatial structures for the dif-  
 165 ferent populations using the *RandomFields* R package (Schlather et al., 2015).  
 166 We define a stationary habitat field with an anisotropic pattern (to simulate a  
 167 depth gradient) and combine it with a temporally dynamic thermal tolerance  
 168 field to imitate two key drivers of population dynamics without modelling the  
 169 processes explicitly. Each population was initialised at a single location, and  
 170 subsequently moved across the entire space according to a probabilistic distri-  
 171 bution based on habitat suitability (represented by the normalised values from  
 172 the GRFs), temperature tolerance and distance from current cell:

$$Pr(C_{wk+1} = J | C_{wk} = I) = \frac{e^{-\lambda \cdot d_{I,J}} \cdot (Hab_{J,p}^2 \cdot Tol_{J,p,wk})}{\sum_{c=1}^C e^{-\lambda \cdot d} \cdot (Hab_{c,p}^2 \cdot Tol_{c,p,wk})} \quad (5)$$

174 Where  $d_{I,J}$  is the euclidean distance between cell  $I$  and cell  $J$ ,  $\lambda$  is a given rate



175 of decay,  $Hab_{c,p}$  is the index of habitat suitability for cell  $c$  and population  $p$ ,  
 176 with  $Tol_{c,p,wk}$  the temperature tolerance for cell  $c$  by population  $p$  in week  $wk$   
 177 (see below).

178

179 During pre-defined weeks of the year the habitat suitability is modified with  
 180 user-defined spawning habitat locations, resulting in each population having  
 181 concentrated areas where spawning takes place. The populations then move to-  
 182 wards these cells in the weeks prior to spawning, resulting in directional move-  
 183 ment towards the spawning grounds.

184

185 A time-varying temperature covariate changes the interaction between time  
 186 and suitable habitat on a weekly time-step. Each population  $p$  was assigned a  
 187 thermal tolerance with mean,  $\mu_p$  and standard deviation,  $\sigma_p$  so that each cell  
 188 and population temperature tolerance is defined that:

$$Tol_{c,p,wk} = \frac{1}{\sqrt{(2\pi \cdot \sigma_p^2)}} \cdot \exp\left(-\frac{(T_{c,wk} - \mu_p)^2}{2 \cdot \sigma_p^2}\right) \quad (6)$$

189 Where  $Tol_{c,p,wk}$  is the tolerance of population  $p$  for cell  $c$  in week  $wk$ ,  $T_{c,wk}$  is  
 190 the temperature in the cell given the week and  $\mu_p$  and  $\sigma_p$  the mean and stan-  
 191 dard deviation of the population temperature tolerance. The variables, their  
 192 meaning and units for population movement is provided in Table 2.

193

194 ~~The final combined process results in a population structure and movement~~  
 195 ~~pattern unique to each population, with population movement occurring on a~~  
 196 ~~weekly basis. The decision to model population movement on a weekly timescale~~  
 197 ~~was to reflect that fish tend to aggregate in species specific locations that have~~  
 198 ~~been observed to last around one to two weeks (Poos et al 2007). Therefore this~~  
 199 ~~process approximated the demographic shifts in fish populations throughout a~~  
 200 ~~year with seasonal spawning patterns (Figure S3).~~

## 201 2.4. Fleet dynamics

202 Fleet dynamics ~~were can be~~ broadly categorised into three components. *Fleet*  
203 *targeting* ~~determined~~*determines* the fleet catch efficiency and preference to-  
204 wards a particular population; *trip-level decisions* ~~determined that~~ *determines*  
205 the initial location to be fished at the beginning of a trip; and *within-trip deci-*  
206 *sions* ~~determined fishing locations, that determines movement from one fishing~~  
207 ~~spot to another~~ within a trip. This results in an explore-exploit strategy ~~was~~  
208 ~~implemented in the model that combined these three components~~ for individual  
209 vessels to maximise their catch from an unknown resource distribution (Bailey  
210 et al., 2019). The decision to use an individual based model for fishing vessels  
211 was taken because fishers are heterogeneous in their location choice behaviour  
212 due to different objectives, risk preference and targeting preference (Van Putten  
213 et al., 2012; Boonstra and Hentati-Sundberg, 2016). Therefore fleet dynamics  
214 are emergent from individual dynamics rather than pre-defined group dynamics.

### 215 2.4.1. Fleet targeting

216 Each fleet of  $n$  vessels was characterised by both a general efficiency,  $Q_{fl}$ ,  
217 and a population specific efficiency,  $Q_{fl,p}$  which are each bound by  $[0,1]$ . The  
218 product of these parameters  $[Q_{fl} \cdot Q_{fl,p}]$  affects the overall catch rates for the fleet  
219 and the preferential targeting of one species over another. This, in combination  
220 with the parameter choice for the step-function defined below (as well as some  
221 randomness from the exploratory fishing process) determined the preference of  
222 fishing locations for the fleet.

### 223 2.4.2. Decision about where to fish at the start of a trip

224 Several studies (for a review see Girardin et al., 2017) have confirmed past  
225 activity and past catch rates are strong predictors of fishing location choice.  
226 For this reason, the fleet dynamics sub-model included a learning component,  
227 where a vessel's initial fishing location in a trip was based on selecting from  
228 previously successful fishing locations. This was achieved by calculating an  
229 expected revenue based on the catches from locations fished in the preceding

trip as well as the same month periods in previous years and the travel costs from the port to the fishing grounds. Then a vessel chooses randomly from the top 70 % of fishing events (defined as the ‘threshold’) in terms of expected profit within that season.

### 2.4.3. *Decision about where to fish within a trip*

Fishing locations within a trip are initially determined by a modified random walk process. As the simulation progresses the within-trip decision become gradually more influenced by experience gained from past fishing locations (as per the initial trip-level location choice), moving location choice towards areas of higher perceived profit. A random walk was chosen for the exploratory fishing process as it is the simplest assumption commonly used in ecology to describe optimal animal search strategy for exploiting heterogeneously distributed prey about which there is uncertain knowledge (Viswanathan et al., 1999). In a random walk, movement is a stochastic process through a series of steps. These steps have a length, and a direction that can either be equal in length or take some other functional form. The direction of the random walk was also correlated (known as ‘persistence’) providing some overall directional movement (Codling et al., 2008).

For our implementation of a random walk directional change is based on a negatively correlated circular distribution where a favourable fishing ground is likely to be “fished back over” by the vessel returning in the direction it came from. The step length (i.e. the distance travelled from the current to the next fishing location) is determined by relating recent fishing success, measured as the summed value of fish caught (revenue,  $Rev$ );

$$Rev_{c,d} = \sum_{p=1}^P L_{c,d,p} \cdot Pr_p \quad (7)$$

where  $L_{c,d,p}$  is landings of a population  $p$ , and  $Pr_p$  price of a population. All population prices were kept the same across fleets and seasons. Here, when fishing is successful vessels remain in a similar location and continue to exploit

the local fishing grounds. When unsuccessful, they move some distance away from the current fishing location. The movement distance retains some degree of stochasticity, that can be controlled separately, but is determined by the relationship:

$$Le = e^{\log(\beta_1) + \log(\beta_2) - \left(\log\left(\frac{\beta_1}{\beta_3}\right)\right) \cdot Rev} \quad (8)$$

Where  $\beta_1$ ,  $\beta_2$  and  $\beta_3$  are parameters determining the shape of the step function in its relation to revenue, so that, a step from  $(x_t, y_t)$  to  $(x_{t+1}, y_{t+1})$  is defined by:

$$\begin{aligned} (x_{t+1}, y_{t+1}) &= x_t + Le \cdot \cos\left(\frac{\pi \cdot Br_{t+1}}{180}\right), \\ y_t &+ Le \cdot \sin\left(\frac{\pi \cdot Br_{t+1}}{180}\right) \end{aligned} \quad (9)$$

when  $Br_t < 180, Br_{t+1} = 180 + \sim vm[(0, 360), k]$   
 $Br_t > 180, Br_{t+1} = 180 - \sim vm[(0, 360), k]$

where  $Le$  is the step length,  $Br_t$  is the bearing at time  $t$ ,  $k$  the concentration parameter from the von Mises distribution that we correlate with the revenue so that  $k = (Rev + 1/RefRev) \cdot max_k$ , where  $max_k$  is the maximum concentration value,  $k$ , and  $RefRev$  is parametrised as for  $\beta_3$  in the step length function. Details of the variables, meaning and units for fleet dynamics are provided in Table 3.

#### 2.4.4. Local population depletion

Where several fishing vessels exploit the same fish population competition is known to play an important role in local distribution of fishing effort (Gillis and Peterman, 1998). If several vessels are fishing on the same patch of fish, local depletion and interference competition will affect fishing location choice of the fleet as a whole (Rijnsdorp, 2000; Poos and Rijnsdorp, 2007a). To account for this behaviour, the fishing sub-model operates spatially on a daily time-step so that for future days the biomass available to the fishery is reduced in the areas fished. The cumulative effect is to make heavily fished areas less attractive as a future fishing location choice as reduced catch rates will be experienced.

## 281 2.5. Fisheries independent survey

282 A fisheries-independent survey is simulated where fishing on a regular grid  
283 begins each year at the same time for a given number of stations (a fixed station  
284 survey design). Catches of the populations at each station are recorded but not  
285 removed from the population (catches are assumed to have negligible impact  
286 on population dynamics). This provides a fishery independent snapshot of the  
287 populations at a regular spatial intervals each year, similar to scientific surveys  
288 undertaken by fisheries research agencies.

289

## 290 2.6. Software: R-package development

291 The simulation framework is implemented in the statistical software package  
292 R (R Core Team, 2017) and available as an R package from the author’s github  
293 site ([www.github.com/pdolder/MixFishSim](https://www.github.com/pdolder/MixFishSim)).

294

## 295 3. Model calibration

296 We calibrate *MixFishSim* to investigate the influence of data aggregation on  
297 spatial inference.

### 298 3.1. Population models

299 We calibrated the simulation model for four example populations with dif-  
300 ferent demographics, growth rates, natural mortality and recruitment (Table 4).  
301 Habitat preference (Figure S4) and temperature (Figures S5, with temperature  
302 tolerance S6) defined to be unique to each population resulting in differently  
303 weekly distribution patterns (Figures S3-S8). In addition, each of the pop-  
304 ulations was assumed to have two defined spawning areas that result in the  
305 populations moving towards these areas in pre-defined weeks (Figure S9) with  
306 population-specific movement rates (Table 4). The population demographics  
307 were defined to broadly represent three mobile low-medium value groundfish

species and one high value species with low mobility, with the dynamics hypothetical but as you might expect to find in a typical demersal fishery.

### 3.2. Fleet calibration

The fleets were calibrated to reflect five different characteristic fisheries with unique exploitation dynamics (Table 5). By setting different catchability coefficients ( $Q_{fl,p}$ ) we create different targeting preferences between the fleets and hence spatial dynamics. The learned random walk process implies that within a fleet different vessels have different spatial distributions based on individual experience. The step function was calibrated dynamically within the simulations as the maximum revenue obtainable was not known beforehand. This was implemented so that vessels take smaller steps when fishing at a location that yields landings value in the top 90th percentile of the value experienced in that year so far (as defined per fleet in Table 5).

Fishing locations were chosen based on random search and, with increasing proportion as time progressed, experience of profitable catches built up in the same month from previous years and from the previous trip. 'Profitable' in this context was defined as the locations where the top 70 % of expected profit would be found given revenue from previous trips and cost of movement to the new fishing location. This probability was based on a logistic sigmoid function with a lower asymptote of 0 and upper asymptote of 0.95, and a growth rate that ensures the upper asymptote (where decisions are mainly based on past knowledge) is reached approximately halfway through the simulation.

### 3.3. Survey settings

The survey simulation was set up with a fixed gridded station design with 100 stations fished each year, starting on day 92 and ending on day 112 (5 stations per day) with same catchability parameter ( $Q_p = 1$ ) for all populations  $p$ . This approximates a real world survey design with limited seasonal and spatial coverage.

338 *3.4. Example research question*

339 To illustrate the capabilities of *MixFishSim*, we investigate the influence of  
340 the temporal and spatial resolution of different data sources on the reduction in  
341 catches of a population given spatial closures. To do so, we set up a simulation  
342 to run for 50 years based on a  $100 \times 100$  square grid (undetermined units), with  
343 five fleets of 20 vessels each and four fish populations. Fishing takes place four  
344 times a day per vessel and five days a week, while population movement is every  
345 week.

346  
347 *How does sampling-derived fisheries data reflect the underlying population*  
348 *structure?*

349  
350 To answer this question we compare different spatial and temporal aggrega-  
351 tions of the true population distributions to:

- 352 a) **fisheries-independent data:** the inferred population density from a  
353 fixed-site sampling survey design as commonly used for fisheries monitor-  
354 ing purposes;
- 355 b) **fisheries-dependent data:** the inferred population density from our  
356 fleet model that includes fishery-induced sampling dynamics.

357 We allow the simulation to run unrestricted for 30 years, then implement  
358 spatial closed areas for the last 20 years of the simulation based on data (either  
359 derived from the commercial catches, fisheries-independent survey or the true  
360 population) used at different spatial and temporal scales.

361  
362 The following steps are undertaken to determine closures:

- 363 1. Extract data source (true population, commercial or survey),
- 364 2. Aggregate according to desired spatial and temporal resolution,

- 365 3. Interpolate across entire area at desired resolution using simple bivariate  
366 interpolation using the *interp* function from the R package *akima* (Akima  
367 and Gebhardt, 2016). This is intended to represent a naive spatial model  
368 of catch rates, without knowledge of the spatial population dynamics.
- 369 4. Close area covering top 5 % of catch rates

370 In total 28 closure scenarios were run that represent combinations of:

- 371 • **data types:** commercial logbook data, survey data and true population,
- 372 • **temporal resolutions:** weekly, monthly and yearly closures,
- 373 • **spatial resolutions:** 1 x 1 grid, 5 x 5 grid, 10 x 10 grid and 20 x 20 grid,
- 374 • **closure basis:** highest 5 % of catch rates for the protected population

375 We implemented a series of spatial closures targeted at reducing fishing mor-  
376 tality on population 3, given the different data sources and spatial and temporal  
377 resolutions above. We use the effectiveness of these closures in reducing fishing  
378 mortality as a way of evaluating the trade-offs in data sources and resolution.  
379 Survey closures were on an annual basis only, as this was the most temporally  
380 resolved survey data available. We evaluated the factors contributing to the suc-  
381 cess of the closures through a regression tree (using the R package *REEMtree*  
382 (Sela and Simonoff, 2011)) to identify the factor most contributing to differences  
383 in fishing mortality before and after the closure.

## 384 4. Results

### 385 4.1. Emergent simulation dynamics

386 Individual habitat preferences and thermal tolerances result in different spa-  
387 tial habitat use for each population (Figure S1) and consequently different sea-  
388 sonal exploitation patterns (Figure S2).

It can be seen from a single vessels movements during a trip that the ves-  
sel exploits three different fishing grounds, each of them multiple times (Figure



2(A)), while across several trips fishing grounds that are further apart are fished (Figure 2 (B)). These different locations relate to areas where the highest revenue were experienced, as shown by Figure 2 (D), where several vessels tracks are overlaid on the revenue field, i.e.

$$Rev_c = \sum_{p=1}^P B_{c,p} \cdot Q_{fl,p} \cdot Pr_p$$

389 Vessels from the same fleet (and therefore targeting preference) may exploit  
 390 some shared and some different fishing grounds depending on their own personal  
 391 experience during the exploratory phase of the fishery (Figure 2 (C)). This  
 392 results from the randomness in the correlated random walk step function, with  
 393 distance moved during the exploitation phase and the direction stochastically  
 394 related to the revenue experienced on the fishing ground (Figure 2 (D)).

#### 395 4.2. How does sampling-derived fisheries data reflect the underlying population 396 structure?

397 The ~~aggregated~~ catch composition ~~aggregated at different spatial resolutions~~  
 398 from each of the data sources (~~which shows~~ average seasonal patterns over a  
 399 ten-year period) highlights different patterns in perceived community structure  
 400 depending on the data source and aggregation level (Figure 3). The finer spatial  
 401 grid for the true population (top left) and commercial data (top middle) show  
 402 visually similar patterns, though there are large unsampled areas in the com-  
 403 mercial data from a lack of fishing activity (particularly in the lower left part  
 404 of the sampling domain). The survey data at this spatial resolution displays  
 405 very sparse information about the spatial distributions of the populations. The  
 406 slightly aggregated data on a 5 x 5 grid shows similar patterns and, while los-  
 407 ing some of the spatial detail, there remains good consistency between the true  
 408 population and the commercial data. Survey data starts to pick out some of the  
 409 similar patterns as the other data sources, but lacks spatiotemporal coverage.  
 410 The spatial catch information on a 10 x 10 and 20 x 20 grid lose a signifi-  
 411 cant amount of information about the spatial resolutions for all data sources,  
 412 and some differences between the survey, commercial and true population data

413 emerge.

414

415 Different perceptions of the proportion of each stock in an area are seen when  
416 we aggregate the data at different timescales, with weekly (top), monthly (mid-  
417 dle) and yearly (bottom) catch compositions from across an aggregated 20 x 20  
418 area showing different patterns (Figure 4). In the true population, the monthly  
419 aggregation captures the major patterns of composition seen in the weekly data  
420 with the percentage of different populations in the catch having similar mean  
421 and standard deviations (Table 7). In the weekly and monthly data population  
422 2 dominates. However, some of the variation was lost when aggregated to an  
423 annual level, as indicated from the lower standard deviations (Table 7).

424

425 The commercial data on a weekly basis shows some of the same patterns as  
426 the true population, though the population 1 (in red) is less well represented  
427 and some weeks are missing catches from the area. Here, weekly and monthly  
428 compositions were nearly identical (Figure 4; Table 7). Again, yearly values  
429 head a similar mean but smaller standard deviation.

430

431 The survey data was only available on an annual basis, and showed again  
432 a slightly different composition from the true population and the commercial  
433 data; in particular a greater proportion of population 4 (Figure 4).

#### 434 4.3. How does data aggregation and source impact on spatial fisheries manage- 435 ment measures?

436 ~~We implemented a spatial closure using the different data sources and spatial  
437 and temporal aggregations as outlined in the protocol in Section 3.4. We used  
438 this to assess the efficacy of a closure in reducing fishing mortality on population  
439 3, given availability of data and its use at different resolutions in order to  
440 evaluate the trade-offs in data sources.~~

441 In most cases the fishery closure was successful in reducing fishing mortality  
442 on the species of interest (population 3; Figure 5). Interestingly the largest re-

443 reductions in fishing mortality happened immediately after the closures, following  
 444 which the fisheries “adapted” to the closures by finding new areas of high abun-  
 445 dance to fish. This led to fishing mortality increasing again, though not to past  
 446 levels (Figure 5). The exception to the success was the closures implemented  
 447 based on the coarsest spatial (20 x 20) and temporal resolution (yearly) that  
 448 was ineffective (i.e. failed to reduce fishing mortality) with all data sources.  
 449 As expected, closures based on the “known” population distribution were most  
 450 effective, with differing degrees of success using the commercial data. Fishing  
 451 mortality rates on the other species changed in different proportions, depending  
 452 on whether the displaced fishing effort moved to areas where the populations  
 453 were found in greater or lesser density.

454  
 455 The factor most contributing to differences in fishing mortality before and  
 456 after the closure was the population (72 % showing that the closures were ef-  
 457 fective for population 3), followed by data resolution (21 %), data type (7 %)  
 458 with the least important factor the timescale ( $< 1$  %). In general the finer the  
 459 spatial resolution of the data used the greater reduction in fishing mortality for  
 460 population 3 after the closures (Figure 6). The notable outliers are the com-  
 461 mercial data at the coarsest spatial resolution (20 x 20) at a yearly and weekly  
 462 timescale, where closures were nearly as effective as the fine-scale resolution. In  
 463 this case the closures were sufficiently large to protect a core area of the habitat  
 464 for the population, but this was achieved in a fairly crude manner by closing a  
 465 large area - including area where the species was not found (Figure 7) that may  
 466 have consequences in terms of restricting the fishery in a much larger area than  
 467 necessary. We found that these trade-offs existed, with high catches maintained  
 468 with an effective closure when the highest resolution data was used, with the  
 469 effect being linear when the true population distribution was known and also  
 470 persisting for closures based on commercial information (Figure 8).

471

## 472 5. Discussion

473 Our study presents a new highly resolved fisheries simulation framework to  
474 evaluate the importance of data scaling and considers potential bias introduced  
475 through data aggregation when using fisheries data to infer spatiotemporal dy-  
476 namics of fish populations. Understanding how fishers exploit multiple hetero-  
477 geneously distributed fish populations with different catch limits or conservation  
478 status requires detailed understanding of the overlap of resources; this is difficult  
479 to achieve using conventional modelling approaches due to species targeting in  
480 fisheries resulting in preferential sampling (Martínez-Minaya et al., 2018). Of-  
481 ten data are aggregated or extrapolated which requires assumptions about the  
482 spatial and temporal scale of processes. Our study explores the assumptions  
483 behind such aggregation and preferential sampling to identify potential impacts  
484 on management advice. With modern management approaches increasingly  
485 employing more nuanced spatiotemporal approaches to maximise productivity  
486 while taking account of both the biological and human processes operating on  
487 different time-frames (Dunn et al., 2016), understanding assumptions behind  
488 the data used - increasingly a combination of logbook and positional informa-  
489 tion from vessel monitoring systems - is vital to ensure measures are effective.

### 491 5.1. Simulation dynamics

492 We employ a simulation approach to model each of the population and fish-  
493 ery dynamics in a hypothetical ‘mixed fishery’, allowing us to i) evaluate the  
494 consequences of different aggregation assumptions on our understanding of the  
495 spatiotemporal distribution of the underlying fish populations, and ii) evaluate  
496 the effectiveness of a spatial closure given those assumptions.

497  
498 Our approach is unique in that it captures fine scale population and fish-  
499 ery dynamics and their interaction in a way not usually possible with real data  
500 and thus not usually considered in fisheries simulations. While other simulation

frameworks seek to model individual vessel dynamics based on inferred dynamics from VMS and logbook records (Bastardie et al., 2010), or as a system to identify measures to meet particular management goals (Bailey et al., 2019), our framework allows users to explore ~~the~~ assumptions in modelling observational data and ~~to~~ evaluate the underlying dynamics of such approaches at ~~a~~ fine spatial and temporal scales. This offers the advantage that larger scale fishery patterns are emergent properties of the system and results can be compared to those obtained under a statistical modelling framework.

Typically, simulation models that treat fish as individuals are focussed on exploring the inter- and intra- specific interactions among fish populations (e.g. OSMOSE; Shin et al. (2004)) in order to understand how they vary over space and time. Our focus was on understanding the strengths and limitations of inference from catch data obtained through commercial fishing activity with fleets exploiting multiple fish populations. ~~This shows how-and~~ realised ~~catch~~ distributions ~~that~~ may differ from the underlying populations, as identified by Gillis et al. (2008). As such, we favoured a minimum realistic model of the fish populations (Plagányi et al., 2014) taking account of environmental but not demographic stochasticity, while incorporating detailed fishing dynamics that take account of different drivers in a mechanistic way.

Demographic stochasticity arises due to individual-level variability in time to reproduction and death. This form of stochasticity is often modelled by drawing random time intervals from a given distribution (Gillespie, 1977). The impact of demographic stochasticity depends on the population size, with the effects expected to decrease with increasing population size (Lande et al., 2010). This contrasts with environmental stochasticity, which affects all population sizes and is present at the population level in our model by variability in recruitment.

We take account of heterogeneity in fleet dynamics due to different preferences and drivers similarly to other approaches (Fulton et al., 2011), but at an

individual vessel rather than fleet level. We do not explicitly define fleets as rational profit maximisers at the outset, but consider there are several stages to development of the fishery; information gathering through search where the resource location is not known, followed by individual learnt behaviour of profitable locations. This provides a realistic model of how fishing patterns are established and maintained to exploit an uncertain resource through an explore-exploit strategy (Mangel and Clark, 1983; Bailey et al., 2019).

## *5.2. How does sampling-derived fisheries data reflect the underlying population structure?*

Our results demonstrate the importance of considering data scale and resolution when using observational data to support management measures. We find that understanding of the community composition dynamics will depend on the level of data aggregation and its important to consider the scale of processes; including population movement rates, habitat uniformity and fishing targeting practices if potential biases in data are to be understood and taken into account (Figures S1, 2).

Our simulation shows that, despite biases introduced through the fishing process, the commercially derived data could still inform on the key spatial patterns in the community structures where the fisheries occurred, which was spatially limited due to the “hotspots” of commercially valuable species being fished. Similarly, despite the even spatial coverage the survey was able to capture some of the same spatial patterns as the true population, but missed others due to gaps between survey stations limiting spatial and temporal coverage (Figure 3). This provides a challenge when modelling unsampled areas in inferring species distribution maps, though these limitations may be overcome by understanding the relationship between the species and habitat covariates where these are known at unsampled locations (Robinson et al., 2011).

561 *5.3. How does data aggregation and source impact on spatial fisheries manage-*  
562 *ment measures?*

563 From our simulations spatial disaggregation was more important than the  
564 temporal disaggregation of the commercial data. This reflects the fact that there  
565 was greater spatial heterogeneity over the spatial domain than experienced in  
566 individual locations over the course of the year (Figure S1).

567  
568 The yearly data assumes the same proportion of each population caught at  
569 any time of the year due to the data aggregation. This assumption introduces  
570 ‘aggregation bias’ as the data may only be representative of some point (or no  
571 point) in time. The monthly data shows some consistency between the real pop-  
572 ulation and commercial data for population 2 - 4, though population 1 remains  
573 under-represented. On an annual basis, interestingly the commercial data un-  
574 der represents the first species (in red) while the survey over represents species  
575 1. This is likely due to the biases in commercial sampling, with the fisheries  
576 not targeting the areas where population 1 are present and the survey sampling  
577 areas where population 1 is more abundant than on average. This indicates that  
578 fixed closures, at the right resolution, when based on commercially derived data  
579 have the potential to reduced fishing mortality. The likely cost of poor spatial  
580 and temporal resolution is associated with reduced effectiveness and potentially  
581 closing fishing opportunities for other fisheries (Figure 8).

582  
583 Two contrasting real world approaches in this respect were the spatial clo-  
584 sures to protect cod in the North Sea. In one example, large scale spatial closures  
585 were implemented with little success due to effort displacement to previously  
586 unfished areas (Dinmore et al., 2003), while in another small scale targeted  
587 spatiotemporal closures were considered to have some effect in reducing cod  
588 mortality without having to disrupt other fisheries substantially (Needle and  
589 Catarino, 2011). These examples emphasise the importance of considering the  
590 right scale and aggregation of data when identifying area closures and the need  
591 to consider changing dynamics in the fisheries in response to such closures.

592

593 Our study showed that fishing rates on other populations also changed (both  
 594 up and down) as a side-effect of closures to protect one species. This indicates  
 595 the importance in considering fishing effort reallocation following spatial clo-  
 596 sures, and our simulation allows us to consider the spatiotemporal reasons for  
 597 these changes.

#### 598 *5.4. Model assumptions and caveats*

599 We modelled the population and fleet dynamic processes to draw inference  
 600 on the importance of data scale and aggregation in understanding and manag-  
 601 ing mixed fisheries and their impact on multiple fish populations. In doing so,  
 602 we necessarily had to make a number of simplifying assumptions.

603

604 Fish populations in our simulations move in pre-defined timescales and ac-  
 605 cording to fixed habitat preferences and temperature gradients (Figures S4, S5).  
 606 Our assumptions in calibrating the model (movement rates, temperature toler-  
 607 ances) will have a direct impact on our conclusions on the relative importance  
 608 of spatial and temporal processes. These assumptions could be explored in a  
 609 future study by varying the parameters and assessing the robustness of our con-  
 610 clusions. For our example application we have chosen movement rates to reflect  
 611 aggregation periods observed in past studies (Poos and Rijnsdorp, 2007b).

612

613 In addition, we have assumed that fishing vessels are not restricted by quota  
 614 and therefore discarding of species for which vessels have no quota or that are  
 615 unwanted is not taken into account. This is likely to be a significant source of  
 616 bias in any inference using commercial data and should also be explored. For  
 617 example, *MixFishSim* could be altered to allow for spatiotemporal appraisal of  
 618 the impact of discarding on fisher behaviour and underlying populations via in-  
 619 clusion as discarding behaviour, or through move-on rules or cessation of fishing  
 620 activity when quota is exhausted.

621



## 622 5.5. Future applications of *MixFishSim*

623 We consider that the increased availability of high resolution catch and lo-  
624 cational information from commercial fisheries will require it to be a key source  
625 of data for ensuring management is implemented at the right scale in future.  
626 For example, identifying hot-spots for bycatch reduction or identifying spatial  
627 overlaps in mixed fisheries (Dolder et al., 2018; Gardner et al., 2008; Little et al.,  
628 2015; Dedman et al., 2015; Ward et al., 2015). Our simulation model has the  
629 potential to test some of the assumptions behind the modelling approaches in  
630 identifying such hotspots and indeed behind spatiotemporal modelling in gen-  
631 eral, (e.g. comparing GAMs, GLMMs, Random Forests and geostatistical mod-  
632 els under different data generation processes as exemplified by Stock et al. (2019)).

633  
634 Other novel applications of our framework could be: testing different sur-  
635 vey designs given multiple species and data generating assumptions (Xu et al.,  
636 2015); commercial index standardisation methods and approaches and under-  
637 standing of appropriate scales and data aggregations and non-proportionality  
638 in catch rate and abundance (Harley et al., 2001; Maunder and Punt, 2004);  
639 exploring assumptions about the distribution of natural mortality and fishing  
640 mortality throughout the year and importance of capturing in-year dynamics  
641 in estimating stock status (Liu and Heino, 2014); at sea sampling scheme de-  
642 signs to deliver unbiased estimates of population parameters (Cotter and Pilling,  
643 2007; Kimura and Somerton, 2006); adaptive management (Walters, 2007; Dunn  
644 et al., 2016); testing the ability of commonly employed fleet dynamics models  
645 such as Random Utility Models to capture fine scale dynamics and understand  
646 their importance (Girardin et al., 2017); and as a detailed operating model in a  
647 management strategy evaluation (Mahévas and Pelletier, 2004).

648

## 649 6. Conclusions

650 *MixFishSim* provides a detailed simulation framework to explore the inter-  
651 action of multiple fisheries exploiting different fish populations. The framework  
652 enables users to evaluate assumptions in modelling commercially derived data  
653 through comparison to the true underlying dynamics at a fine spatial and tem-  
654 poral scale. Understanding these dynamics, the limitations of the data and any  
655 potential biases that may be introduced when making inference on spatiotempo-  
656 ral interactions will enable users to identify weaknesses in modelling approaches  
657 and identify where data collection is needed to strengthen inference.

658  
659 Our application shows that inference on community dynamics may change  
660 depending on the scale of data aggregation. There is an important balance in  
661 ensuring that the data are sufficiently spatially and temporally disaggregated  
662 that the main features of the data are captured, yet maintaining enough data  
663 coverage that the features can be distinguished. We found in our application  
664 that there was greater spatial heterogeneity than temporal heterogeneity and  
665 that when using aggregated data to define spatial closures coarser temporal reso-  
666 lution (months instead of weeks) could still achieve the same results in reducing  
667 exploitation rates of a vulnerable species at the highest temporal resolution  
668 data. Conversely, reducing the spatial resolution had a negative effect on the  
669 effectiveness of the measures (though importantly, there was still some benefit  
670 even with coarse spatial resolution).

671  
672 While any findings are likely to be case specific, our findings emphasise the  
673 need to understand population demographics, habitat use and movement rates  
674 in designing any closure scenario based on observational sampling. This infor-  
675 mation can then be used to set the bounds on data aggregation used in modelling  
676 studies aimed at informing the management measures.

677  
678 *MixFishSim* has numerous potential additional applications as it enables

679 the user to apply methods to a fisheries system where there is detailed under-  
680 standing of underlying spatiotemporal dynamics. This enables identification of  
681 weaknesses or limitations which would not be possible otherwise. In future, we  
682 recommend use of the framework to test hypotheses that are otherwise unable  
683 to be analysed using real world data due to limitations of data collection. That  
684 way the knowledge gained through simulation can inform the future design of  
685 management measures.

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## 692 **Appendices**

Table 1: Description of variables for population and recruitment dynamics sub-modules.

Variable	Meaning	Units
<b>Population dynamics</b>		
<i>Delay-difference model</i>		
$B_{c,d}$	Biomass in cell $c$ and day $d$	kg
$Z_{c,d}$	Total mortality in cell $c$ for day $d$	-
$R_{c,\bar{y}}$	Annually recruited fish in cell	yr <sup>-1</sup>
$\rho$	Brody's growth coefficient	yr <sup>-1</sup>
$Wt_R$	Weight of a fully recruited fish	kg
$Wt_{R-1}$	Weight of a pre-recruit fish	kg
$\alpha_d$	Proportion of annually recruited fish recruited during day $d$	-
<i>Baranov catch equation</i>		
$C_{c,d}$	Catch from cell $c$ for day $d$	kg
$F_{c,d}$	Instantaneous rate of fishing mortality in cell $c$ on day $d$	-
$M_{c,d}$	Instantaneous rate of natural mortality in cell $c$ on day $d$	-
$B_{c,d}$	Biomass in cell $c$ on day $d$	kg
<b>Recruitment dynamics</b>		
$\tilde{R}_{c,d}$	is the recruitment in cell $c$ for day $d$	$d^{-1}$
$B_{c,d}$	biomass in cell $c$ for day $d$	$d^{-1}$
$\alpha$	the maximum recruitment rate (Beverton Holt) or maximum productivity per spawner (Ricker)	kg
$\beta$	the stock size required to produce half the maximum rate of recruitment (Beverton Holt) or density dependent reduction in productivity per capita of SSB	kg

Table 2: Description of variables for population movement sub-module.

Variable	Meaning	Units
<i>Thermal tolerance</i>		
$T_{c,wk}$	Temperature for cell $c$ in week $wk$	$^{\circ}\text{C}$
$\mu_p$	Mean of the thermal tolerance for population $p$	$^{\circ}\text{C}$
$\sigma_p$	Standard deviation of thermal tolerance for population $p$	$^{\circ}\text{C}$
<i>Population movement model</i>		
$\lambda$	Decay rate for population movement	-
$Hab_{c,p}$	Habitat suitability for cell $c$ and population $p$	-
$Tol_{c,wk,p}$	Thermal tolerance for in cell $c$ at week $wk$ for population $p$	-
$d_{I,J}$	Euclidean distance between cell $I$ and cell $J$	-

Table 3: Description of variables for fleet dynamics sub-module.

Variable	Meaning	Units
$Rev$	Revenue from fishing tow	$\text{€}$
$L_p$	Landings of population $p$	kg
$Pr_p$	Average price of population $p$	$\text{€ kg}^{-1}$
$Le$	Step length for vessel	-
$Br$	Bearing	degrees
$k$	Concentration parameter for von mises distribution	-
$\beta_1$	shape parameter for step function	-
$\beta_2$	shape parameter for step function	-
$\beta_3$	shape parameter for step function	-

Table 4: Population dynamics and movement parameter settings.

Parameter	Pop 1	Pop 2	Pop 3	Pop 4
Habitat quality				
Matérn $\nu$	1/0.015	1/0.05	1/0.01	1/0.005
Matérn $\kappa$	1	2	1	1
Anisotropy	1.5,3,-3,4	1,2,-1,2	2.5,1,-1,2	0.1,2,-1,0.2
Spawning areas (bound box)	40,50,40,50; 80,90,60,70	50,60,30,40; 80,90,90,90	30,34,10,20; 60,70,20,30	50,55,80,85; 30,40,30,40
Spawning multiplier = 10				
Movement $\lambda = 0.1$				
Population dynamics				
Starting Biomass	1e5	2e5	1e5	1e4
Beverton-Holt Recruit $\alpha$	6	27	18	0.3
Beverton-Holt Recruit $\beta$	4	4	11	0.5
Beverton-Holt Recruit $\sigma^2$	0.7	0.6	0.7	0.6
Recruit week	13-16	12-16	14-16	16-20
Spawn week	16-18	16-19	16-18	18-20
$K = 0.3$				
$wt = 1$				
$wt_{d-1} = 0.1$				
M (annual)	0.2	0.1	0.2	0.1
Movement dynamics				
$\mu_p$	12	15	17	14
$\sigma_p^2$	8	9	7	10

Table 5: Fleet dynamics parameter setting.

Parameter	Fleet 1	Fleet 2	Fleet 3	Fleet 4	Fleet 5
Targeting preferences	pop 2/4	pop 1/3	-	pop 4	pop 2/3
Price $Pr_p1 = 100$					
Price $Pr_p2 = 200$					
Price $Pr_p3 = 350$					
Price $Pr_p4 = 600$					
$Q_p$	0.01	0.02	0.02	0.01	0.01
$Q_p$	0.02	0.01	0.02	0.01	0.03
$Q_p$	0.01	0.02	0.02	0.01	0.02
$Q_p$	0.02	0.01	0.02	0.05	0.01
Exploitation dynamics					
step function $\beta_1$	1	2	1	2	3
step function $\beta_2$	10	15	8	12	7
step function $\beta_3$ , the land- ings value $n$ th quantile	90	90	85	90	80
step function $rate$	20	30	25	35	20
Past Knowledge = TRUE					
Threshold	0.7	0.7	0.7	0.7	0.7
Fuel Cost	3	2	5	2	1

Table 6: Fishing mortality effects of the closure scenarios on population 3 (ordered by most effective first). The fishing mortality rate before the closure was 1.08.

Scenario No	F after closure	% F change	data type	timescale	resolution
9	0.29	-73.47	true Population	weekly	1.00
10	0.29	-72.94	true Population	monthly	1.00
11	0.35	-68.04	true Population	yearly	1.00
45	0.58	-46.70	commercial	yearly	20.00
1	0.58	-46.21	commercial	weekly	1.00
23	0.59	-45.27	true Population	weekly	5.00
2	0.59	-45.06	commercial	monthly	1.00
7	0.60	-44.48	survey	yearly	1.00
24	0.61	-43.20	true Population	monthly	5.00
3	0.64	-40.82	commercial	yearly	1.00
25	0.65	-39.94	true Population	yearly	5.00
17	0.67	-38.11	commercial	yearly	5.00
15	0.71	-34.38	commercial	weekly	5.00
43	0.71	-34.31	commercial	weekly	20.00
16	0.73	-32.58	commercial	monthly	5.00
51	0.78	-27.92	true Population	weekly	20.00
37	0.78	-27.76	true Population	weekly	10.00
39	0.79	-26.98	true Population	yearly	10.00
38	0.81	-25.47	true Population	monthly	10.00
21	0.81	-25.21	survey	yearly	5.00
35	0.81	-25.05	survey	yearly	10.00
44	0.87	-19.91	commercial	monthly	20.00
52	0.88	-18.39	true Population	monthly	20.00
30	0.96	-11.06	commercial	monthly	10.00
29	0.98	-9.80	commercial	weekly	10.00
31	1.03	-4.36	commercial	yearly	10.00



53	1.06	-1.64	true Population	yearly	20.00
49	1.07	-1.01	survey	yearly	20.00

Table 7: Mean and standard deviation of proportions of each species at different levels of temporal aggregation

Data type	Timescale	Population 1	Population 2	Population 3	Population 4
commercial	monthly	0.047(0.014)	94.435(1.47)	3.122(1.468)	2.396(0.444)
commercial	weekly	0.047(0.016)	94.426(1.514)	3.117(1.563)	2.411(0.498)
commercial	yearly	0.051(0.001)	94.388(0.205)	3.021(0.175)	2.539(0.046)
True Population	monthly	9.225(3.872)	83.287(5.522)	3.624(1.151)	3.864(1.519)
True Population	weekly	9.358(3.992)	83.165(5.596)	3.567(1.233)	3.91(1.592)
True Population	yearly	9.899(0.173)	82.25(0.308)	3.821(0.119)	4.031(0.05)
survey	yearly	0.372(0.005)	87.667(0.193)	0.729(0.02)	11.232(0.172)

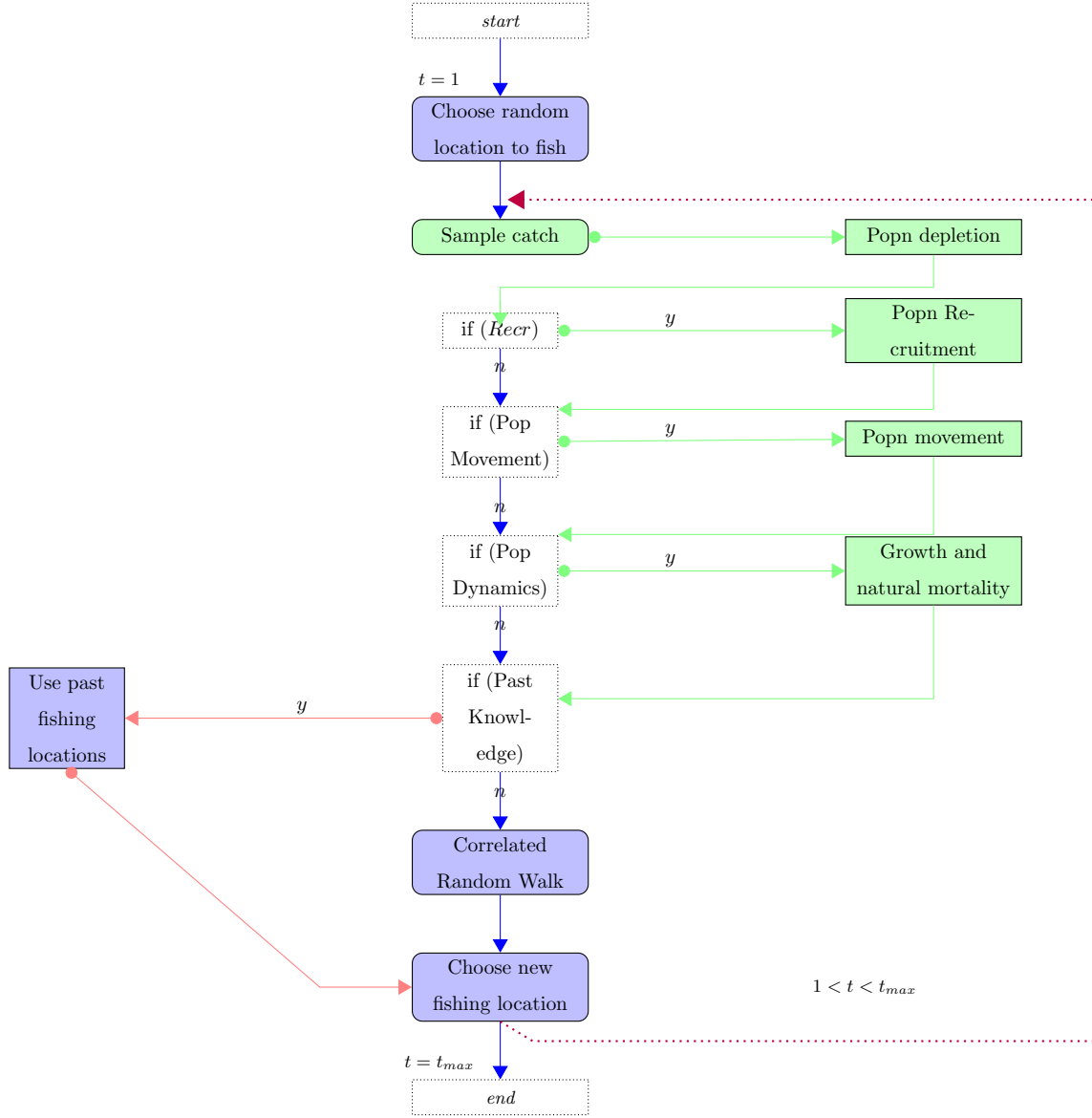


Figure 1: Schematic overview of the simulation model. Blue boxes indicate fleet dynamics processes, the green boxes population dynamics processes while the white boxes are the time steps at which processes occur;  $t = \text{tow}$ ,  $t_{max}$  is the total number of tows; (Recr), (Pop Movement), (Pop Dynamics) logic gates for recruitment periods, population movement and population dynamics for each of the populations, (Past Knowledge) a switch whether to use a random (exploratory) or past knowledge (exploitation) fishing strategy.

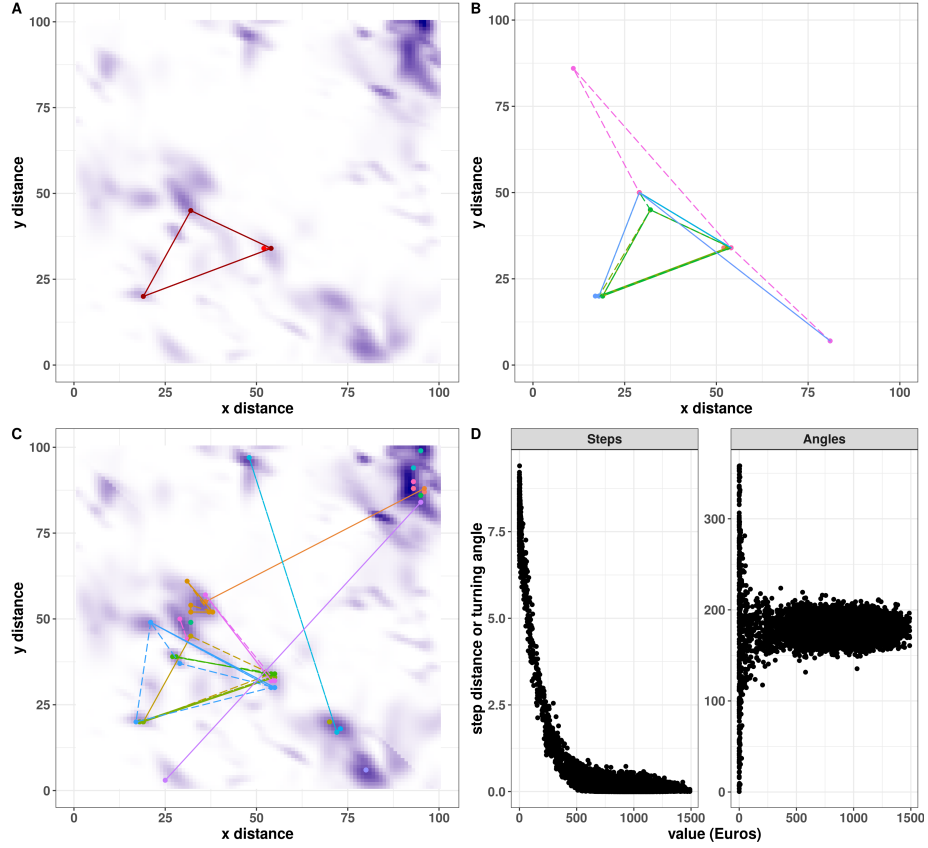


Figure 2: (A) The fishing locations (points) and movements (lines) of a single vessel during a trip overlaid on the revenue of a fishing site (landings  $\times$  price; darker purple = higher revenue); (B) the fishing locations of the vessel over several trips (value field changes over the period so not shown). Note that movements are a mixture of correlated random walk (solid lines) and experience-based (dashed lines), and that the field is wrapped on a torus so that opposite sides of the spatial domain are considered spatially close; (C) the locations of multiple vessels from the same fleet overlaid on the value field, (D) the realised step distance and turning angles for a single vessel over the simulation.

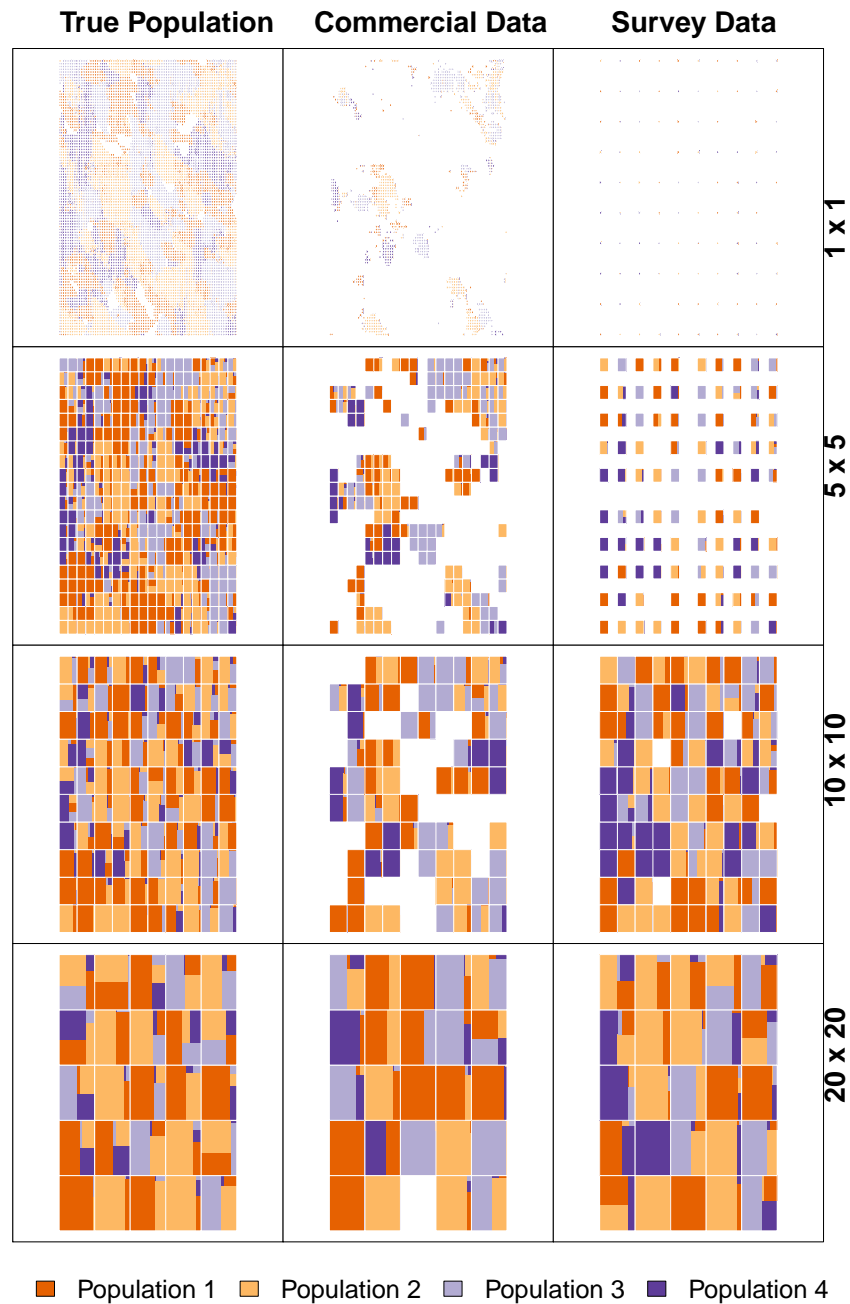


Figure 3: [Colour] Data aggregation at different spatial resolutions over a ten year period. The figure shows catch composition at each spatial unit represented by a square pie chart of the four populations. The area of each colour is proportionate to the weight of each population caught in that unit. Figure produced using the R package 'mapplots' (Gerritsen (2014)).

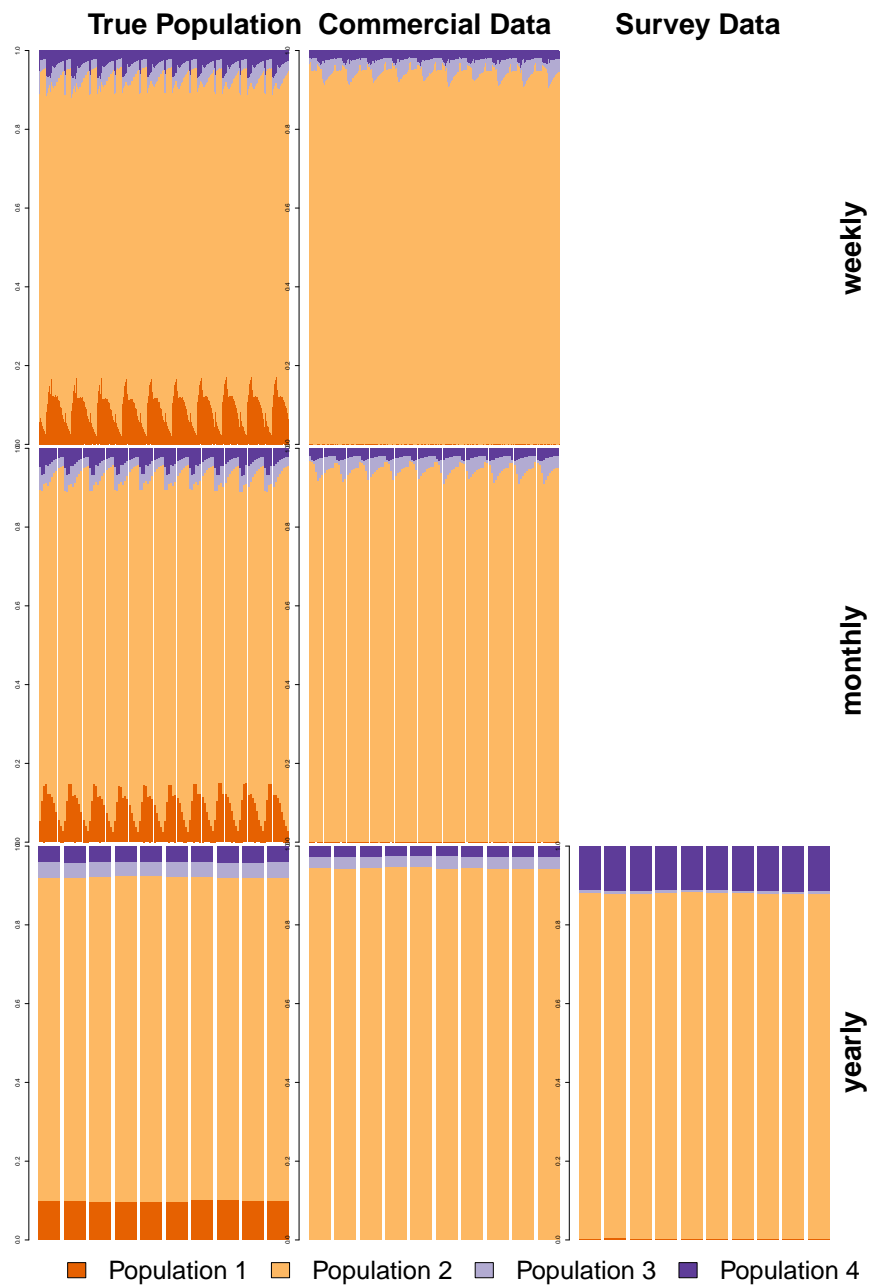


Figure 4: [Colour]Proportion of each population (y axis) for data aggregated at different temporal resolutions. Data is aggregated over a ten-year period for an area 20 x 20. Each bar represents either a week, month or year respectively.

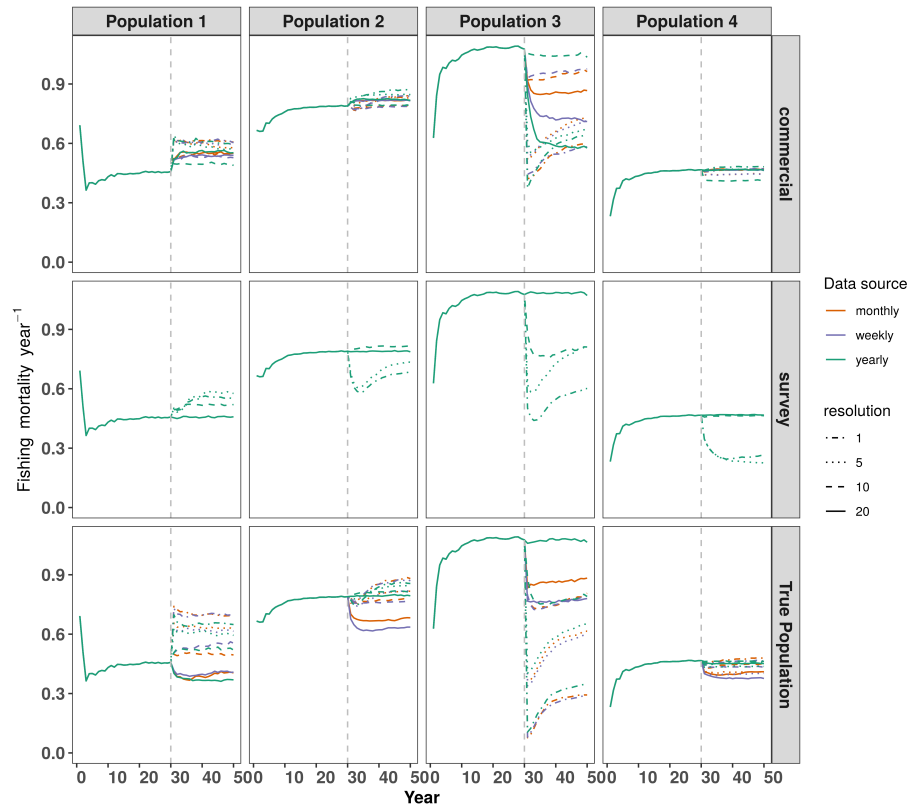


Figure 5: [Colour]Comparison of closure scenarios effect on fishing mortality trends. Line colour denotes timescale, while linestyle denotes spatial resolution. The vertical dashed line indicates the onset of the spatial closures.

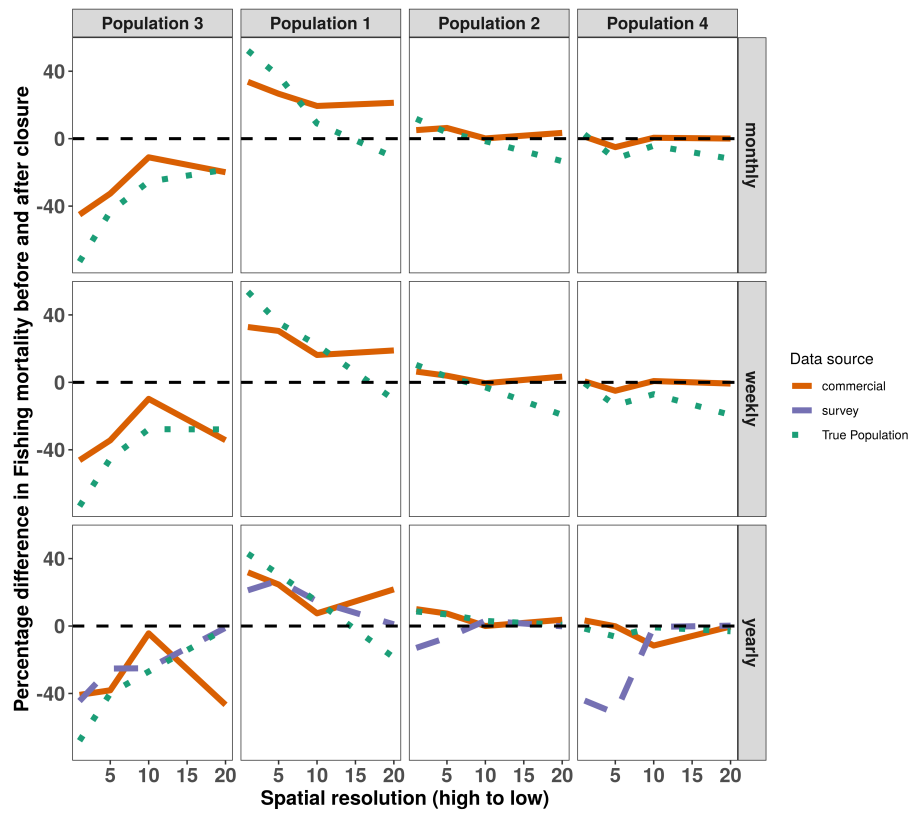


Figure 6: Comparison of closure scenario effectiveness based on different spatial and temporal resolutions.



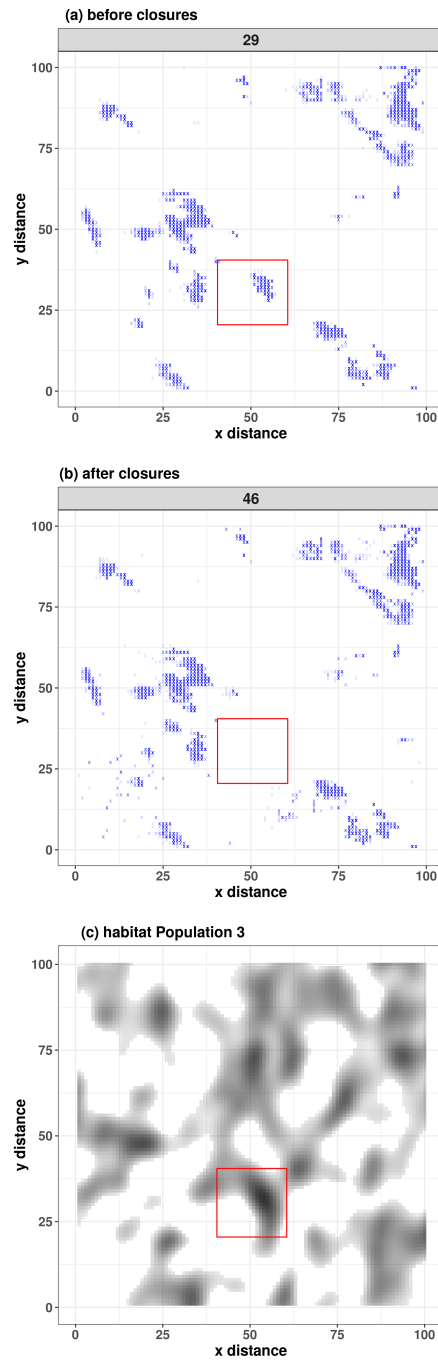


Figure 7: The location of fishing effort, (a) before the spatial closure and (b) after the spatial closure (years in panel), and (c) the suitable habitat for population 3. The site of the closure can be seen in the red box on all three panels.

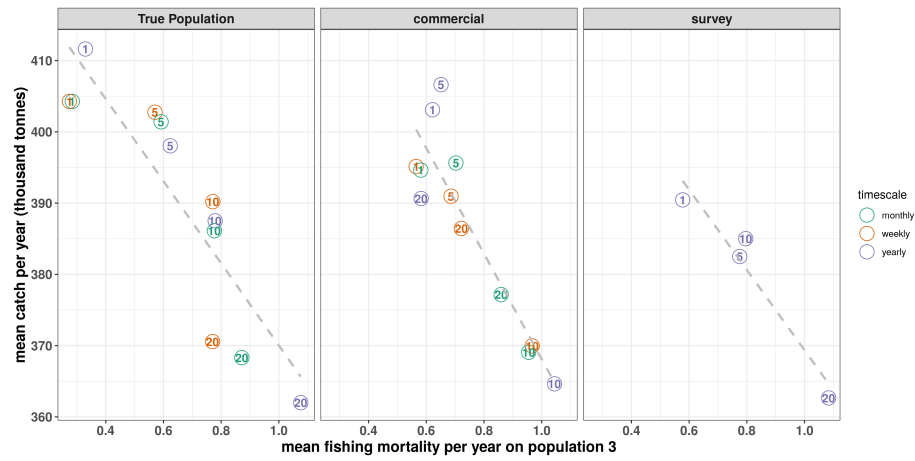


Figure 8: [Colour]Effectiveness of closure with regards to reducing fishing mortality on protected population (further left on x-axis is best) and maintaining high catches in the fishery (highest on y-axis is best). The numbers indicate the spatial resolution of the data, while grey lines indicate the direction of the trade-off between reducing fishing mortality and overall catches.

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