## General approach

We developed an operating model consisting of a spatially-explicit population dynamics model coupled with a stochastic vessel dynamics. The model is used to simulate CPUE data for which we applied different methods for handling rare observations and derive a CPUE index

## The operating model

A spatially-explicit model (30 x 30 cells; *na*=900) including multiple fish stocks (*k* stocks), coupled with vessel dynamics model is used to generate the CPUE data (Figures 1 and 2). The model works as follows. For each year of an arbitrarily chosen 30-year projection (*ny*=30) period: (1) fishing effort is distributed to each area given the population distributions at the start of the year, and the catch in each cell is calculated. Catch is allocated based on the expected revenue of the grid cell while including some uncertainty. (2) population abundance by cell is adjusted for catch and growth, and (3) fish are redistributed spatially based on movement probabilities. This generates catch and effort data on the 30 x 30 grid which are then used for CPUE standardization.

The underlying population dynamics for each species *s,* are governed by the Schaefer model (Schaefer 1954) with movement dynamics controlled by the species-specific depth preference and mobility. The population biomass *Bs,a,t* for species *s,* in grid *a* at time *t* changes through time as a function of the catch *Cs,a,t*, the intrinsic rate of growth of the stock *rs*, the carrying capacity of species *s* for grid *a, Ks,a*, the biomass of animals emigrating *EMs,a,t*, and the biomass of animals immigrating *IMs,a,t*:

 (1)

The probability *Ms,ab*of species *s* moving from grid *a* to grid *b* is a function of (i) the mobility of the species *s* - modeled with an exponential decaying function that depends on the distance *dab* and a rate parameter *λs* (Moilanen and Nieminen 2002, Ono et al. 2015), (ii) species depth preference – modeled with a lognormal distribution with parameters (*μs,d, σs,d*) where *zi* is the depth of grid *i* (Ono et al. 2015), and (iii) species distribution range (x-axis wide) - modeled using a lognormal distribution with parameters (*μs,r, σs,r*) where *xi* is the x-axis coordinate of the grid *i* (Table 1).

 (2)

Depth (*Z*) is simulated as Gaussian random field with an exponential decay covariance function that depends on distance *d* between grids, with an overall variance τ*2*, and a rate  that controls the rate at which the spatial correlation declines with distance (eq 3).

 (3)

The minimum of the simulated value is then added to keep *Z* positive.

The biomass of emigrants from grid *a* (*EMa,t*) and that of immigrants to grid *a* (*IMa,t*) at time *t* is calculated as:

 ;  (4)

Species biomass in each area *a,* at the start of the simulation is assumed to be at carrying capacity *Ks,a*, which is obtained by determining the stationary distribution of the population over areas (by iterative method).

* 1. Fleet dynamics

The total amount of nominal effort across all grids and all vessels during year *t, E.,t,* is generated from a lognormal distribution with mean given by a logistic function of time and a CV of 0.2, where is the final year effort:

For t∈[1;T],  ⎣⎦ (5)

These integer effort levels are then distributed randomly among thirty vessels (*nv*=30). Each vessel has its own catchability coefficient *qv* generated from a lognormal distribution with parameters (=0.05, CVq=0.05).

Vessel *v* distributes its effortduring year *t*, *E,t,v*, to each grid *a* with a probability *πa,t,v* that depends on the mean expected revenue in each grid (*ps* is the price of species *s*).

 (6)

The amount of effort (trips) for vessel *v* in grid *a* during year *t*, *Ea,t,v*, follows a multinomial distribution with probability *πa,t,v*. :

 (7)

We introduced some randomness in the catch by sampling the realized catchability for trip *e* by vessel *v, q’v,e* , from a Tweedie distribution with a mean *µ=qv* and values for *p* and *Φ* of 1.2 and 0.1 respectively. This allowed simulating zero-inflated CPUE data as it is usually the case in practice (Maunder and Punt 2004). The total (over vessels) catch *Cs,a,t* for species *s* in grid *a* and time *t* is determined as follows:

 (8)

*Cs,a,t* is finally redistributed among vessels and fishing events to generate catch per unit effort for the *e*th trip by vessel *v*, in grid *a*, during year *t*, *Cs,a,t,v,e,* used for the CPUE standardization.

 (9)

Reference:

Maunder, M.N., Punt, A.E., 2004. Standardizing catch and effort data: a review of recent approaches. Fish. Res. 70, 141–159. doi:10.1016/j.fishres.2004.08.002

Moilanen, A., Nieminen, M., 2002. simple connectivity measures in spatial ecology. Ecology 83, 1131–1145.

Ono, K., Punt, A.E., and Hilborn, R. 2015. Think outside the grids: An objective approach to define spatial strata for catch and effort analysis. Fish. Res. 170: 89–101. doi:10.1016/j.fishres.2015.05.021.

Schaefer, M.B., 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. Bull. 1, 27–56, IATCC.

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### Population dynamics

The underlying population dynamics are governed by a deterministic logistic model with a yearly time step, referred to as a Schaefer model in fisheries (Schaefer 1954), with movement dynamics controlled by habitat (depth) preference and mobility. This model has often been used in combination with indices of abundance, to estimate population abundance (Hilborn and Walters 1992). The population biomass *Ba,t* in area *a* at time *t* evolves through time as a function of the catch *Ca,t* in the area *a* during year *t*, the intrinsic rate of growth of the stock *r*, the “regional” carrying capacity *Ka,*, the biomass of animals emigrating *EMa,t*, and the biomass of animals immigrating *IMa,t*:

1. 

The movement between areas during year *t* is calculated as follows. The probability *Mab*of moving from area *a* to area *b* is a function of the Euclidian distance *dab=*||*a-b*|| between the centers of gravity of the two areas and the relative preference of the habitat in area *b* compared to that in the rest of areas. Fish migration is represented by an exponential decay function that depends on the distance *dab* and rate *λ* (Moilanen and Nieminen 2002, Ono et al. 2013) and fish depth preference follows a lognormal distribution with parameters (*μ, σ*) where *zx* is the depth of area *x* (Ono et al. 2013) (Table 1).

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Depth is simulated from a multivariate normal distribution with a mean that changes linearly with respect to the y-coordinate of the areas and an exponential decay covariance function that depends on distance *d* between areas (eq 3). The linear increase in depth with the y-coordinate mimics a coastline (represented by the x-coordinate) that slowly increases in depth with the distance from coast.

1. 

where Z is the depth variable (Figure 1, upper panels), *yb* is the y-coordinate of area *b*, *α* is the trend parameter for depth (also determines the patchiness of depth distribution), τ*2*is the variance parameter, and  controls the rate at which the spatial correlation declines with distance (Table 1). The simulated depth is then standardized so that it spans a specific range (Table 1).

The biomass of emigrants from cell *a* (*EMa,t*) and that of immigrants to cell *a* (*IMa,t*) at time *t* is calculated as:

1.  ; 

The biomass in each area at the start of the simulation is assumed to be *Ka*, obtained by running the model without catch until the biomass stabilizes.

### The fleet dynamics

The total amount of nominal effort across all areas and all vessels during year *t, Et,* is generated from a lognormal distribution with mean given by a logistic function of time and a CV of 0.2, where is the final year effort, i.e.:

1. ⎣⎦

These integer effort levels are then distributed randomly among twenty vessels (*nv*=20). Each vessel has its own catchability coefficient *qv* generated from a lognormal distribution with parameters (=0.1, CVq=0.2). The differences in *qv* among vessels reflects differences in vessel characteristics or skipper skill among vessels. The *qv* are time-invariant, but are equal to 0 in the closed areas i.e . Area closure is implemented in this study by closing certain depth zones to fishing, as is often done in the West coast of the United States (Table 1).

Vessel *v* distributes its effortduring year *t*, *E,t,v*, to each fishing ground *a* with a probability *pa,t,v* that depends on the mean expected catch in each area. This approach is a stochastic version of the so-called “gravity model” (Caddy, 1975). It is assumed that vessels have perfect information about the biomass in each fishing ground, but their catch rate is variable.

1. 

The amount of effort (shots) for vessel *v* in area *a* during year *t*, *Ea,t,v*, follows a multinomial distribution with probability *pa,t,v*. :

1. 

Observation error is accounted for by sampling the realized catchability for shot *e* by vessel *v, q’v,e* , from a Tweedie distribution with a mean *µ=qv* and values for *p* and *Φ* of 1.2 and 0.1 respectively. The Tweedie distribution belongs to the exponential family, and has mean *μ* and variance . It is a continuous distribution with an added mass at 0 when 1<*pv*<2. This distribution is therefore a good candidate to simulate zero-inflated CPUE data, as it is often observed in practice (Maunder and Punt 2004). The total catch *Ca,t* in area *a* and time *t* is determined as follows:

1. 

In order to generate catch per unit effort for the *e*th shot by vessel *v*, in area *a*, during year *t*, *Ca,t,v,e,* used for the CPUE standardization, *Ca,t* is redistributed among vessels and fishing events as follows:

1. 