## 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.